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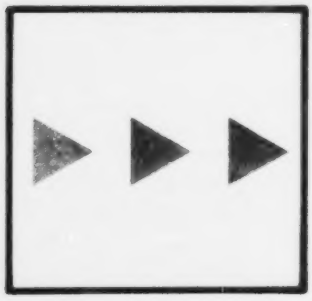

STATE OF THE ART REVIEW OF NDE TECHNIQUE FOR ON-LINE INSPECTION OF PIPELINES FOR SUBCRITICAL CRACKS

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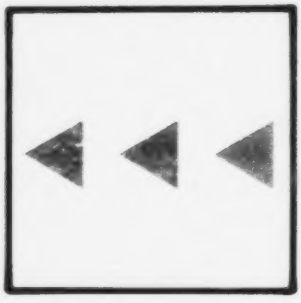

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FINAL REPORT

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STATE OF THE ART REVIEW OF NDE TECHNIQUE FOR ON-LINE INSPECTION OF PIPELINES FOR SUBCRITICAL CRACKS

FINAL REPORT

by

M. MACECEK

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State of the Art Review of NDE Techniques For On-Line Inspection of Pipelines For Subcritical Cracks

1.0 Introduction

The Welding Institute of Canada (WIC) was awarded this contract on behalf of CANMET, Department of Energy, Mines and Resources. A state of the art review of the methods applicable to measurements of subcritical flaws in pipelines using intelligent pigs is the subject of this report. The survey describes in detail the available literature, opinions, and experiences of some workers in the oil and gas industries, and indicates areas that require additional research.

2.0 Defect Types

Defects of a critical nature may be encountered during both the construction and operation of pipelines. The most serious of these are time-dependent flaws which can, during the life of a line, lead to catastrophic failure. The statistical survey (Appendix 1) shows that field failures are caused almost entirely by external factors; only about 20% of the failures can be attributed to material and weld defects. Even so, the economic penalty for a failure may be prohibitively high because of the downtime of the system. The question of safety is also important too;

most of the pipeline right-of-way, however, lies in remote and less populous parts of Canada, where safety is not an immediate cause for concern.

Defects of any importance that can occur are:

- mechanical damage to the line
- buckling, denting
- corrosion
- wall thinning
- weld defects, viz:
    - cracks
    - lack of fusion defects
    - misalignment
    - porosity
    - undercutting
    - residual stresses or
    - externally induced stresses

Of these defects, cracks have the most serious consequences and are not tolerated in any form at all by applicable codes.

The failure rate is high in the older pipelines, now entering the final phase of their expected life-span, but it should be emphasized that in the construction of new lines, inspection is a very thorough procedure. The inspection of a new line under construction is a comparatively easy undertaking since access from both sides of the pipe is possible. However, on-line inspection presents a formidable challenge to prevailing

NDE methods. The inner wall of the pipes are contaminated by corrosion products, oil sediments, and foreign bodies, and access to the pipe is possible only between the entry and retrieval points which are many miles apart. Several NDE methods are now available and some of them have been proven commercially feasible.

3.0 NDE Methods Used

The following methods have been applied to the inspection of pipes and pipelines:

- visual
- photographic
- mechanical
- radiographic
- ultrasonic (elastic wave)
- acoustic emission
- magnetic particle
- magnetic flux leakage
- eddy currents
- holographic
- residual magnetization
- field perturbation by external field

These methods are described in detail below.

3.1 Visual Inspection

A welding inspector who has the knowledge and experience to recognize that an approved welding procedure is being correctly applied must ensure that welding takes place under conditions which will allow for its correct application. On completion of the weld, visual inspection can identify surface imperfections which, depending on the standard required, may need to be rectified. In addition, a skilled inspector should be able to identify the cause and even the individual responsible for the defect. The drawback of the method is that it requires physical entry into the interior of the pipe and can detect only surface flaws. It is therefore not practical for small diameter lines, and for on-line inspection in general, except when used to evaluate photographs.

3.2 Photographic

Peabody Pipeline Services have developed a photographic pig capable of inspecting the inside diameter pipeline wall for either erosion or corrosion occurring at pipe bends, and examining instances or pitting in circumferential welds and in the heat affected zones, besides locating corrosion caused by fluid puddles in low areas of pipe. The system can take 750 B & W or color pictures with 90° - 140° field in 16in. - 36 in. lines ([1],[2]). It can operate at pressures up to 1600 psi (Appendix 2).

The high-resolution photographs reveal:

- erosion and corrosion at pipe bends
- pitting in circumferential welds and heat-affected areas

- corrosion caused by puddles in low lying areas.

The pig can travel up to 300 m (1,000 ft) from the point of entry at 15 m/min (55 fpm). The most beneficial uses were reported for visual inspection of the internal coating of the offshore lines carrying corrosive materials such as H_2S.

An analogous version of this system uses a closed circuit television camera (CCTV) system. The two systems, however, are not meant for long journeys between entry and retrieval points. Because the unbilical cable is not long, the method is best applied to pipes of small diameter (3).

3.3 Holographic Techniques

Acoustical holography has not yet been applied to the testing of pipelines, but optical holographic flaw visualization has been successfully applied to the testing of pipeline and plant piping components.

The method works as follows:

A holocamera is set to obtain the hologram of a device in a relaxed condition, i.e. without pressure or stress. An additional hologram is then taken at operational pressure or equivalent stress. The interference pattern visualized by the camera reveals the flawed region. High accuracy under field conditions was obtained (even with high frequency changes) (4).

As a method for studies of line components, the technique is acceptable and perhaps advantageous, but its use is minimal during on-line inspection. The field applicability of optical holographic techniques to line pipe and weld inspection is therefore unrealistic.

Some restrictions apply to acoustical holographic techniques as well [5]. Appendix 3 shows the technique and its associated hardware.

3.4 Mechanical

After construction is complete, the dimensions of a pipe can reveal any significant damage caused by outside forces. A device which can measure and record pipe dimensions is the T.D. Williamson Inc. "Kaliper Pig."

TDW's Kaliper Pig is a mechanical device that locates, measures, and records changes along the inside diameter of the pipeline, and detects dents and alterations in the diameter of the pipeline. TDW also claims that it will detect abrupt changes of 1/8" or more in wall thicknesses. Short-length diameter reductions of less than 1/2" or expanded pipe cannot generally be discerned. Normal locating accuracy of pipe diameter reductions is usually $\pm$0.5% of the distance from known location markers. Electromagnets on the Kaliper Pig could improve the capability of the equipment for the accurate marking of location.

The pig can record and measure all diameter reductions. These include dents, buckles, flat spots, etc.

T.D. Williamson and other organizations have used this technique with considerable success(6). Despite the simplicity of the method, its applicaton can prevent many unnecessary failures due to extensive deformations in the pipe.

3.5 Radiographic Techniques

X-ray and gamma-ray radiography are the most common inspection techniques employed during actual construction. The existing codes CSA 184, CSA 183, and API 1104 prescribe 100% inspection during the constructon of pipelines. The technique is simple and fast. It provides a permanent record, and is relatively easy to interpret.

Two techniques are basic to radiography: the double-wall, single image (DWSI) technique and the single-wall technique. The double-wall technique, shown in Figure 1a and c, employs the film and source of radiation outside the pipe. The single-wall technique, shown in Figure 1b, uses the source of radiation inside and at the centre of the pipe, with the film placed outside. It has the ability, when using a panoramic X-ray tube head, to record the entire weld circumference in a single exposure, with the help of a radiographic film of the same length. In

contrast, the DWSI technique requires multiple exposures to cover the weld circumference, which is time-consuming as it is necessary to penetrate both pipe walls. The distance from the source of radiation to film is greater than the pipe diameter, and consequently requires at least four times the exposure time necessary than when the source is at the centre of the pipe. This, added to the multiple exposures required to completely examine the weld, brings the exposure time to about 20 times that of a single exposure. While a panoramic x-ray exposure will take 2-5 min.,the four double wall exposures covering the whole 36 inch diameter weld may take an hour.

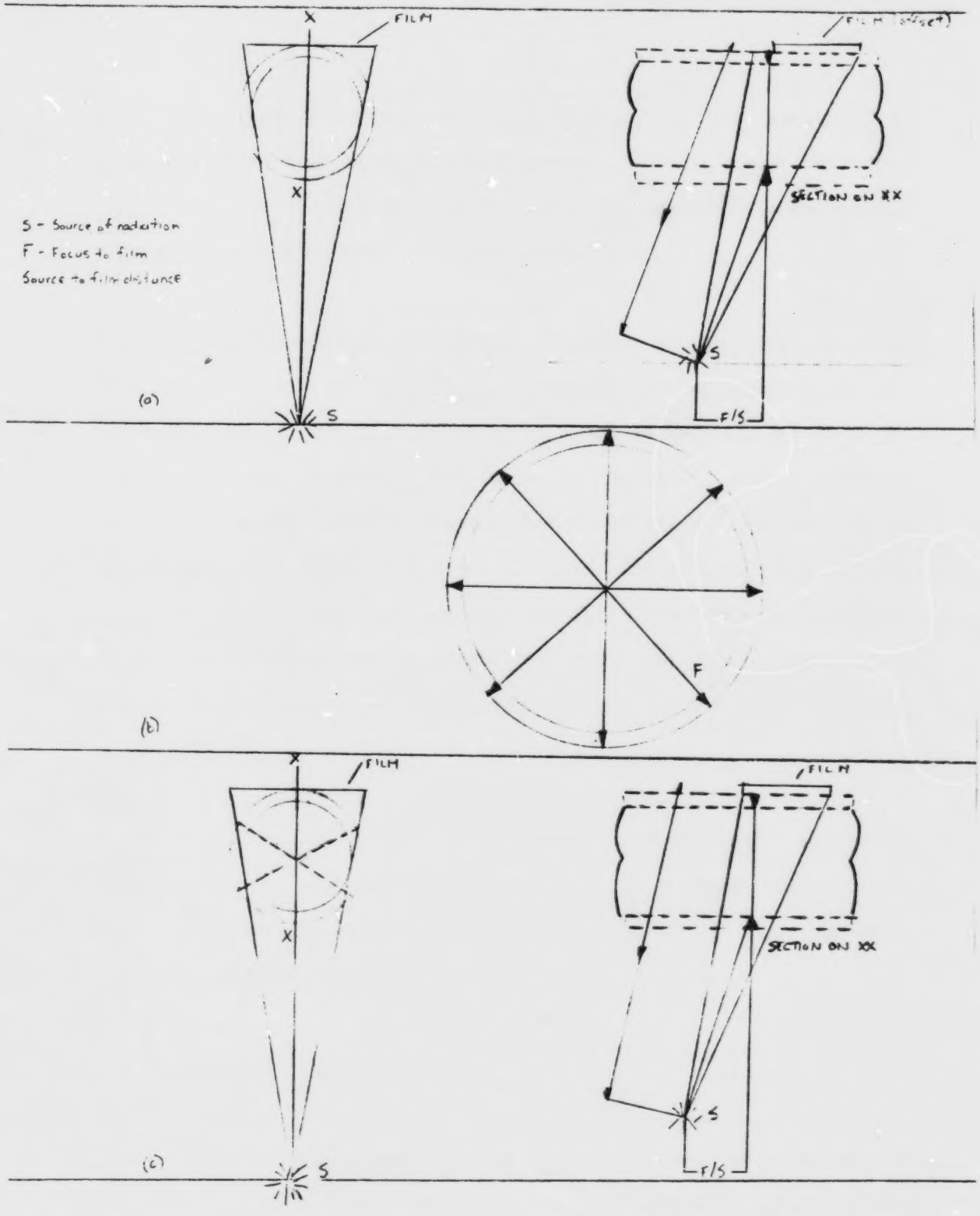

Figure 1: Basic radiographic techniques
(a) double wall, double image.
(b) panoramic, and
(c) double wall, single image.

Both x-ray and gamma-ray sources are used in the inspection of pipelines. The most commonly used gamma source is the Ir 192 which has an energy of approximately 400 kV. In comparison with optimum energy x-rays, this results in a lower contrast.

The film can be replaced by another recording medium, e.g. an x-ray sensitive image intensifier, vidicon, conversion screen, electron channel multiplier, etc. Such an application of these refinements can have the additional benefit of placing the image in real time. Image enhancing techniques can be used to improve the definition and contrast of the radiographs. Both image differentiation and image integration or even image subtraction can yield a high quality image, making it easy to detect the flaw. Computer image processing can also be applied for further image enhancement. A detailed account of the above technique is available elsewhere ([3],[7]).

When considering the method as a technique for in-service inspection, radiography has a severe limitation in that it requires access to the pipe. This method cannot be used for buried or off-shore pipelines, except along their exposed sections.

3.6 Electrical Resistance Methods

The measurement of electrical conductivity (resistance) can yield valuable information about the irregularities in the pipe material. Figure 2 shows

how the method works. The two probes introduce current into the piece, thus creating an electrical field. The additional sensing probes register zero voltage if the material is homogeneous. Any flaw (e.g., crack, corrosion, etc.) will cause a disturbance in the electrical field. The change can be interpreted as having been caused by the flaw, and calibration curves can then be established. The depth of a crack can be determined to an accuracy of close to 0.5 mm on regular shapes. The method is simple, provides a permanent record, and can be automated ([8]).

Its application to on-line inspection, however, is not realistic since:

- measurements are confined to small areas
- the method is sensitive to the quality of the surface
- the speed of inspection is relatively slow.

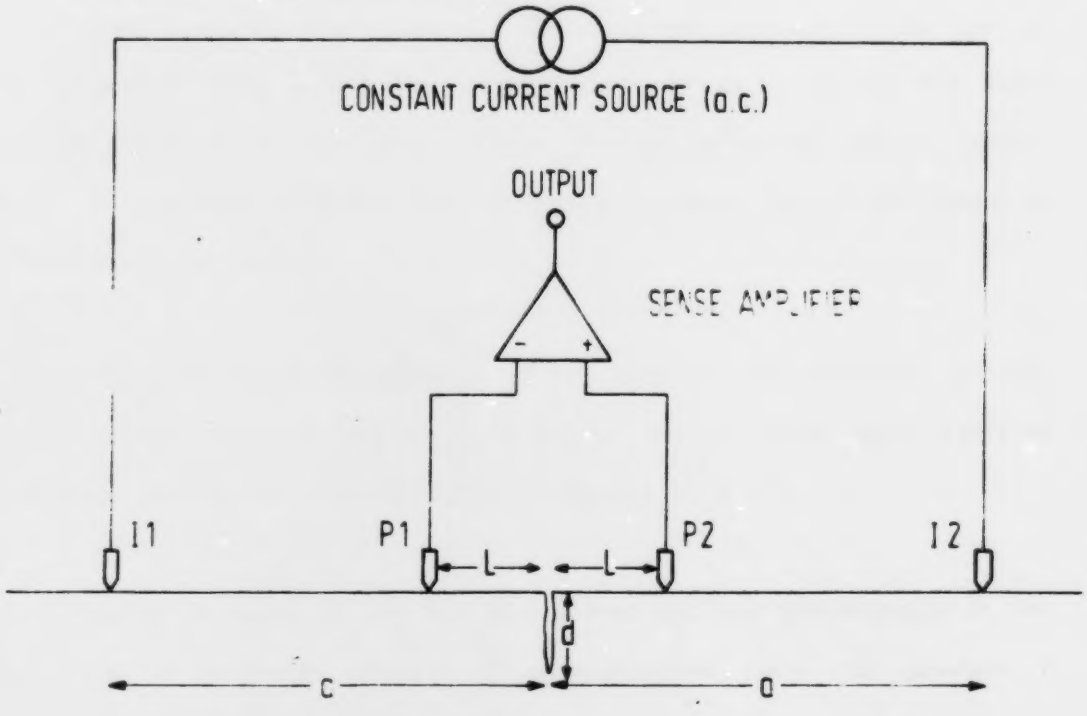

Figure 2: Principle of the electrical conductivity method.

The method can be regarded as a back-up tool to resolve the marginal cases of cracking and corrosion. Its ability to accurately detect and size up cracks under field conditions has yet to be proven.

3.7 Magnetic Methods

Magnetic methods are among the oldest and most pervasive of NDE techniques.

For many years, magnetic powders have found wide acceptance as reliable indicators of relatively large flaws and defects found in components and assemblies manufactured from ferrous metals. The age of automation has brought important new ways of detecting the magnetic leakage flux associated with defects at or near the surface of a magnetized ferromagnetic material. Scanning the surface of the part to be inspected with a suitable magnetometer probe is among the more popular methods of detection. These procedures go by various names, such as magnetic leakage flux, magnetic leakage field, and magnetic perturbation methods.

A complete and detailed account of the methods for detecting leakage fields can be found in the state of the art survey "NDE Applications of Magnetic Leakage Field Methods," by Beissner et al ([9]).

This method is based on the fact that a near surface discontinuity in the geometry or magnetic anomaly of a magnetized body will produce a localized perturbation in the magnetic field outside the test piece.

The first application of this principle of flaw detection was used in the magnetic particle method.

3.7.1 Magnetic Particle Method

This method was developed around 1930 and has now several variations. The method makes use of a fine powder of iron particles which is applied to the surface of a magnetized specimen. The particles are attracted by magnetic field gradients in the vicinity of flaws. They tend to adhere to the surface in such regions, thus giving an indication of the flaw (Figure 3). Many variations are now available, with the original "dry powder method" being augmented by a "wet process" whereby the powder is diluted in the emulsion, which makes the deposition easier. The fluorescent additives can make even a hair-line crack visible ([9]).

The newest developments in this field include the use of magnetized rubber, which can be used underwater ([10]).

The disadvantage of this method is the lack of a permanent quantitative record. In addition, visual inspection of the surface limits the method to easily-accessible surfaces.

Its applicability to the on-line inspection of pipelines is questionable.

3.7.2 Magnetic Flux Leakage Methods

The magnetic flux leakage method is the dominant technique used for the inspection of pipelines at the present time. The method is relatively simple and well adapted to field conditions ([11]).

The principle of the technique can be easily understood with the help of Figure 3.

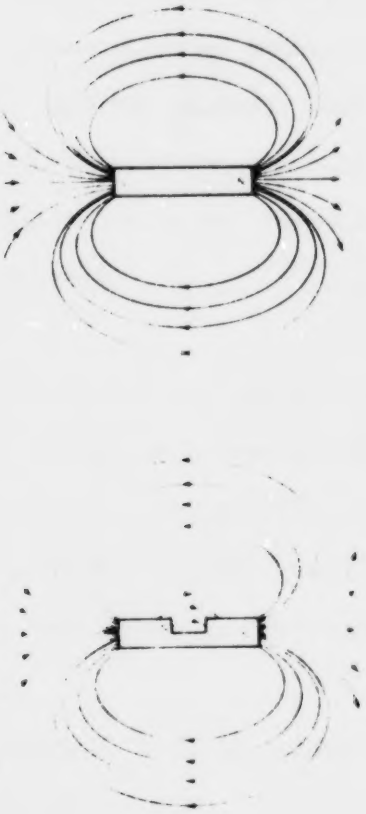

Figure 3: Origin of Defect Leakage Field (Ref. 9).

The top of the figure shows the uniform magnetic rod, which can be said to be made up of a large number of elementary magnets aligned with the direction of magnetization. Inside the material, each pole is exactly complemented by the presence of an adjacent pole of opposite polarity. As a consequence, no external magnetic field results from the interior magnets. On the surface, however, the uncompensated magnetic poles produce a magnetic field in the region surrounding the sample, as shown by the flux lines in Figure 3.

The presence of a slot creates two surfaces with uncompensated poles, with the anomaly also producing a localized field in the vicinity of the slot. This additional field, represented by extra flux lines on the bottom in Figure 3, is defined as the leakage field associated with the slot which is observed even at low flux densities.

The quantitative description is more complex since the magnetic field changes in the vicinity of the flaw. Generally, two distinct sources of the magnetic leakage field are associated with the flaw. One source is the distribution of uncompensated poles on the flaw surface, and the other is the volume, related to changes in the permeability of the material near the flaw. The field is affected by several factors, viz:

- change of magnetic permeability with the magnetic flux
- velocity of movement of magnetic field creating eddy current, thus altering the penetration
- the relation between poles and size of defect, which indicates the possibility of by-passing the leakage field around the defect

A detailed mathematical treatment of the field for a simplified case model can be found elsewhere [11].

Sensors are used to pick up the perturbations in the magnetic leakage flux associated with defects. Typically, they are divided into three groups: magnetic particle, magnetographic, and magnetometric.

Magnetic particle sensing was addressed in the previous section. The magnetographic method takes an indirect approach. The method uses a magnetic tape pressed against the specimen, thereby picking up a magnetic imprint of any leakage field present. The tape is later scanned by a magnetometer to produce a hard copy of the visual image.

Magnetometric methods are used to scan a specimen directly, thus providing a map of the field produced by the defect. A Hall-effect sensor and the flux gate magnetometer are used for the detection of the leakage field.

Figure 4 shows the measurement of the flux leakage by a search coil, while Figure 5 shows the signal and shape during a linear scan.

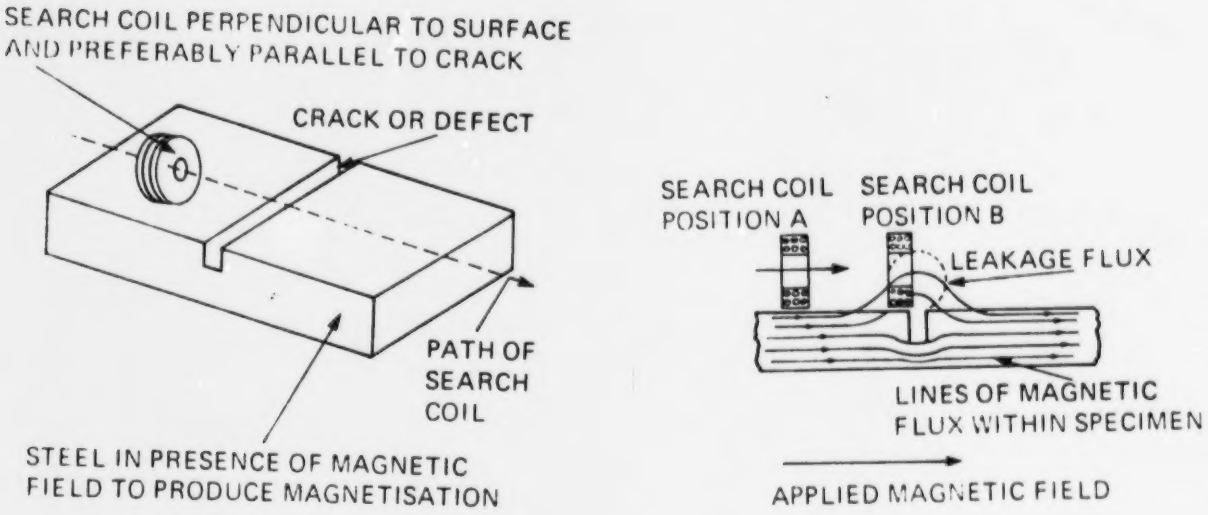

Figure 4: Measurements of the magnetic flux leakage by search coil

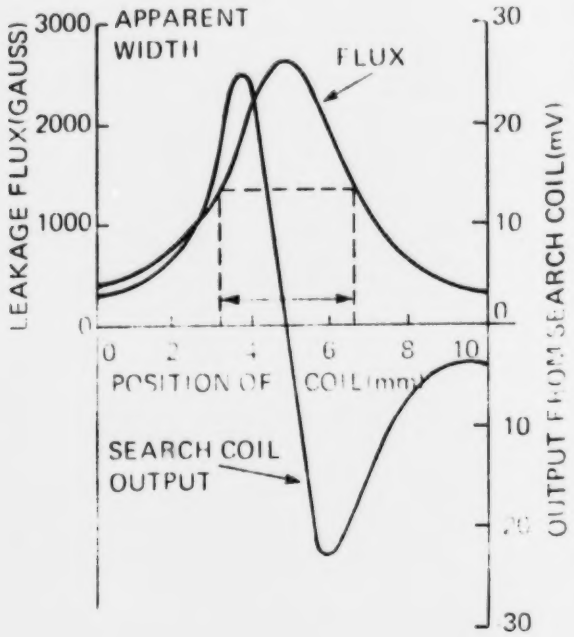

Figure 5: Signal shape during a linear scan

An extensive effort has been made to characterize certain defects, e.g.,

- magnetic signal peak vs flaw size:
- magnetic signal vs orientation
- magnetic signal vs defect type, etc.
- magnetic signal vs distance from the surface

Some of the problems yield an analytical solution, while for others numerical methods are employed. A considerable amount of literature has recently been compiled to deal with the above problem. The technique is advantageous for the identification of defects, namely, the distinguishing of fatigue cracks from inclusions, slots, etc.

Extensive research has been followed by commercial ventures of which two, Linalog and Vectolog, have succeeded and will be described in detail.

3.7.3 Linalog Inspection Pig

The Linalog inspection pig is manufactured by the AMF tuboscope. The unit has a successful track record and close to 100,000 miles of field experience. The overall appearance is shown in Appendix 4.

The unit has an electromagnet to produce the magnetic field which saturates the pipe wall. This extends the thickness range of the equipment. The Linalog is a free-swimming pig with a run time of up to 40 hours for 8 inch to 40 inch lines. The distance (position) can be

measured to ± 0.1% and the system can operate in hostile environments such as H_2S, etc. (12)

Different models are available to inspect different diameters and different wall thicknesses (Appendix 4).

3.7.4 Vetcolog Pig

The Vetcolog pig produced by Vetco Pipeline Services is a sophisticated inspection device using permanent magnets, propelled by the product flow, and may be used without the interruption of service. It provides a permanent record of the severity and location of such flaws as:

- corrosion pitting
- mechanical damage
- gouges
- mill defect
- wrinkle bends
- hard spots
- hydrogen blisters

The Vetcolog pigs are designed for line diameters of 8 inch through 48 inch. The movement of the system is traced by special magnetic tracers (magnets used for reference), and in offshore applications, by acoustical means. A special light-weight electronic playback system is placed close to the site to convert the signals on the magnetic tape into

a script log. The script log is interpreted on the spot and corrective action can be taken if required.

In addition, a final report and log is produced at the central log interpretation facility. More detailed information about the system is given in Appendix 5. The merits and pitfalls of the system will be discussed later in this report.

3.7.5 TransCanada PipeLines Pig

TransCanada PipeLines started their developments in this area approximately ten years ago when dents, external corrosion, and other defects were found in their lines. The AMF tuboscope vehicle which was then available was long and heavy, and required special entry and retrieval points.

TCPL developed (in-house) a different design which is light, short, and is propelled by the pressurized gas in the line (13). Two models are now available:

- ID Model which inspects the internal wall of the pipe for internal deformation, internal wall thinning, etc. The field penetrates the wall but it is too weak to be of any value.
- EML- (External Metal Loss) aimed at the detection of external corrosion has much higher sensitivity and penetrates the wall.

TCPL's experience with the ID model is excellent. The position marking is done by an electromagnetic generator, i.e., reference is above ground which is an improvement on systems.

The nature of the technique causes a strong signal response for a sharp change in geometry. The continuous gradual change will produce a weak signal at the same level as the noise. For this reason, the pig is not intended as a quantitative tool. In addition, the old pipes may contain magnetic anomalies caused by the mill operation which can seriously affect the results.

At present, the activity at the TCPL Laboratory centres around these areas:

- reading of old magnetic tapes to improve the analysis of data from dirty pipes
- computer pulser signal processing of the data
- sensor development to improve the signal-to-noise (S/N) ratio
- defect identification and classification

The mechanical design and data logging is well designed and engineered. The company does not intend to commercialize the pig, but is willing to apply it under special circumstances.

3.7.6 British Gas Corporation Activity

British Gas Corporation (BGC) is a self-regulatory company operating some 8500 miles of pipeline with diameters varying from 12 inch to 42 inch. Some of these lines originated in the 1950's and a clear need for an inspection system was seen by BGC. This resulted in the establishment of an "On-line Inspection Centre" at Cramlington which now employs some 200 people dedicated to on-line inspection (14,15,16,17).

Since the commercially available pigs were not sophisticated enough, a decision to develop their own tools was taken by BGC.

The fiscal commitment is said to be over $100 million. The objectives include:

- no tool interference in the operation of the pipeline
- detection of all defects
- classification of all spurious defects
- area and depth description of all found defects
- found defects must be capable of being located when digging a 10 ft square hole

The first pig is based on magnetic flux leakage principles, and uses extensive computer data processing. The aim is to have real-time presentation of data.

The second pig is based on elastic wave principles and is aimed at detecting longitudinal cracks, such as stress corrosion cracking. The test vehicles are in their final stages of development and very little technical information is available. A paper (14) given in Houston, Texas, is only a promotional announcement. The atmosphere of extreme secrecy, which is dictated by commercial interests, gives rise to suspicions and doubts regarding some of the BGC claims. Whether or not the system will be made commercially available outside BGC in the near future is not yet clear. Magnetic methods are being augmented by elastic wave techniques and are gaining wide acceptance.

3.8 Eddy Current Testing

The eddy current technique is based on the process of inducing electrical currents into a conductive material and allowing the interaction currents to act upon the material. This interaction is described by Maxwell equations. Although the technique as such is old, the introduction of the impedance plane representation of eddy current tests in 1950, has given it enough sophistication to be utilized as a versatile inspection tool.

It is important to note that direct contact with the sample is not required, that the tests are nondestructive, and that a volumetric inspection for flaws is possible; the limitations of the process will be described in the following section.

3.8.1 Some Principles of the Eddy Current Technique

The basic eddy current testing equipment consists of a driving coil, connected with an alternating current source (.5kHz to 2MHz) and a receiving coil, connected with an impedance measuring device (often by a bridge arrangement).

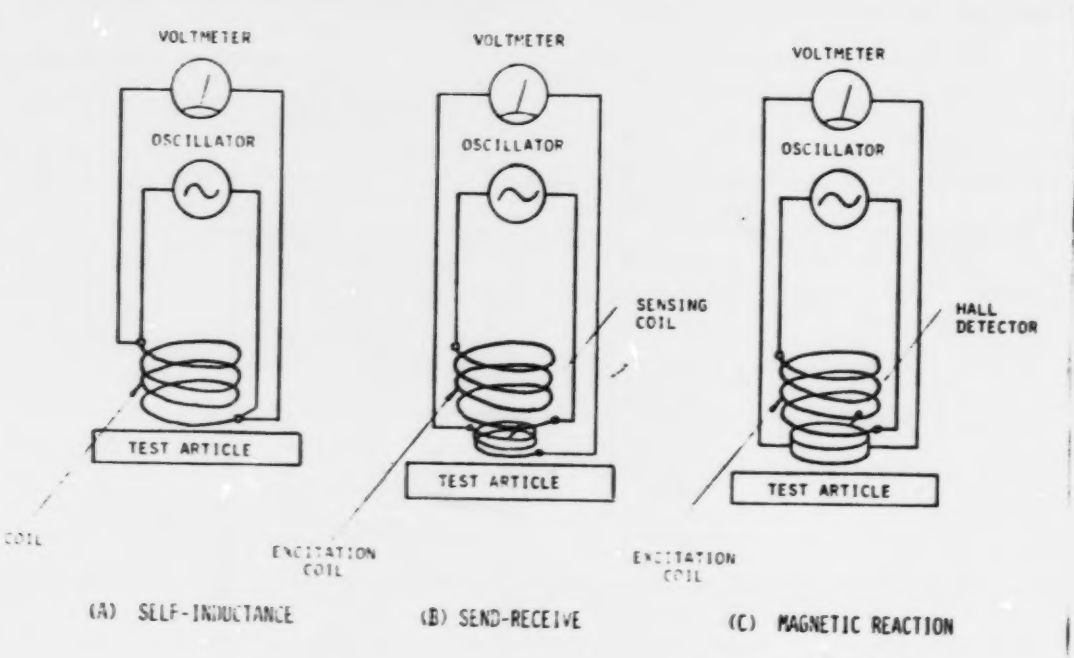

Figure 6: Eddy-current test equipment

The coil induces eddy currents in the test sample over a penetration depth which is inversely proportional to the square root of the product of the electrical conductivity, the magnetic permeability, and the frequency. Only changes within this penetration depth will significantly affect the impedance of the receiving coil.

A typical impedance diagram is shown in Figure 7. Any physical situation is represented by a point on the impedance plane. Changes in conductivity, permeability and lift-off (coil-sample distance) will move this point to a new position. The interpretation of these signals is somewhat complex and sometimes two different explanations of the same signal are possible.

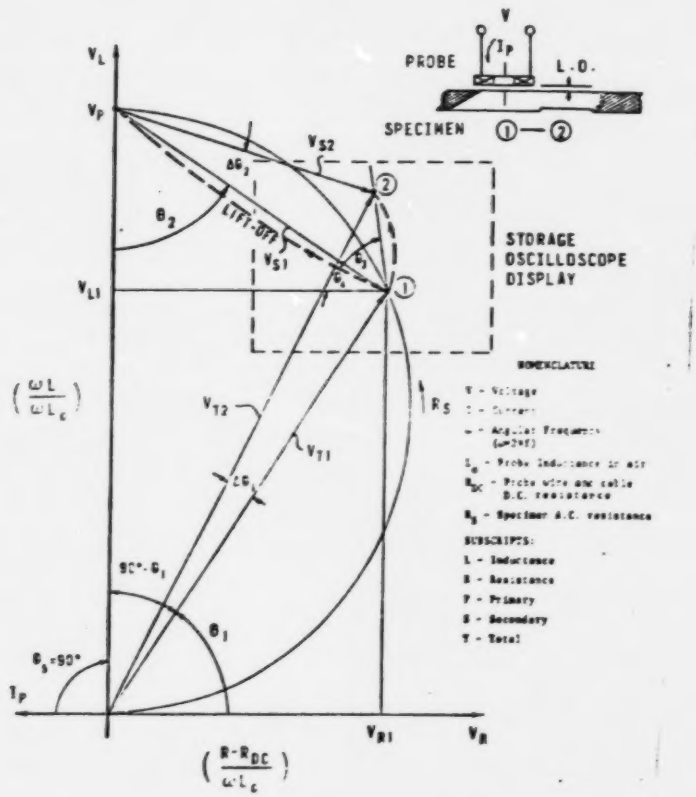

Figure 7: Display of defect signals.

3.8.2 Eddy Current Inspection of Ferromagnetic Material

A complete review of the research in eddy current inspection of ferromagnetic material is beyond the scope of this study. A survey of this kind would be useful, but this report is confined to essential observations only.

The problems encountered in eddy current inspection of ferromagnetic components in pipelines are severe. They are related to the penetration depth, the preponderance of variations in magnetic permeability over other effects (such as defects, resistance and lift-off), and the non-linearity of the magnetic permeability with the applied field.

The most common method in the eddy current inspection of ferromagnetic material is to superimpose a bias field until the material is completely saturated. By utilizing permanent magnets, Chalk River Nuclear Laboratories designed probes for the inspection of Monel tubing; magnetic analysis of other kinds uses large, often cooled, saturating probes (DC current) to minimize the effects of magnetic permeability.

Information about the procedures cannot always be easily obtained, as in the case of Reluxcontrol and the Dr. Forster Institute. However, it can be ascertained that their emphasis also is on coil design.

While the techniques mentioned above have been moderately successful in minimizing the effect of permeability fluctuations, the problem still seems

to await complete resolution. More sophisticated signal processing (multifrequency, pattern recognition, and matched filtering) might be considered in the future.

3.9 Ultrasonic Methods

Ultrasonic methods are newer in the inspection of pipelines but offer some unique capabilities, especially for the inspection of welds.

This section will deal with the ultrasonic techniques as applied to the inspection of pipelines with the emphasis on the on-line inspection.

3.9.1 Defect Types for UT

Due to its nature, the UT methods are most suitable to detect:

- wall thinning
- corrosion in the wall
- cracks and other two-dimensional flaws in pipes and welds
- misalignment (high-low condition)

UT techniques are not used at present to detect the mechanical deformation of the pipe. Access from either the inside or the outside of the pipe is used, with the latter used mostly in the construction stage.

3.9.2 Commercial UT Testing Systems

Several commercial UT testing systems are now available which have been designed specifically for the pipeline applications (24). We can briefly list four systems viz:

- RTD Bandscan (25)
- P-scan system (26)
- Sonomatic System (27)
- WIC internal undercut scanner (28)

In addition to the above, some systems developed for the nuclear and space applications are available. These will be applicable with slight modifications.

The systems are used in the construction of a line for inspection to the API 1104 code. The systems work either with longitudinal or shear waves and either with contact gap or immersion coupling.

None of the ultrasonic systems were applied to the on-line inspection of pipelines.

The above commercial systems can be readily applied to the construction stage since they are applied to the pipe from the outside.

Figures 8 and 9 show the appearance of the four systems when used in the construction of a line.

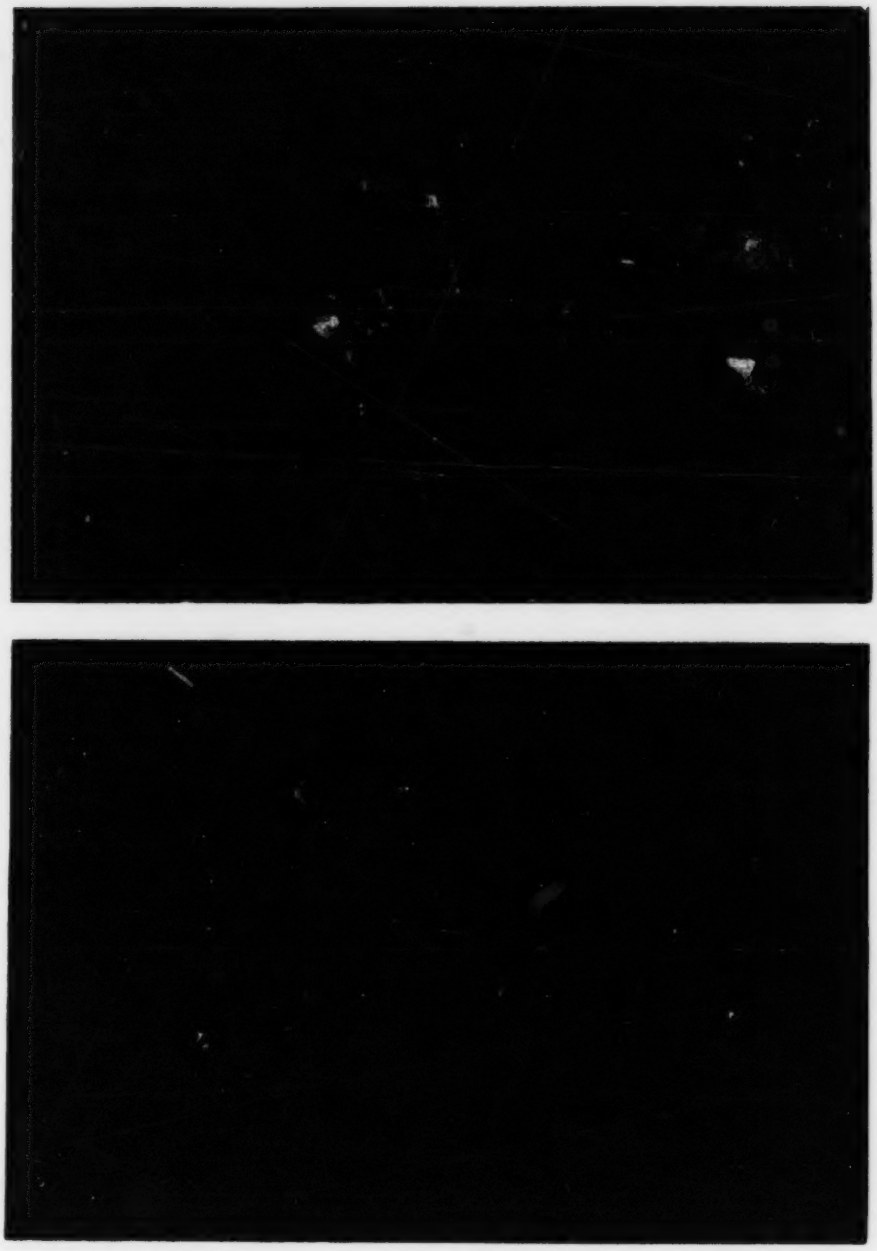

Figure 8: View of the RTD Bandscan mounted on the pipe X (top) SGS Sonomatics - UPS1108 scanner (bottom)

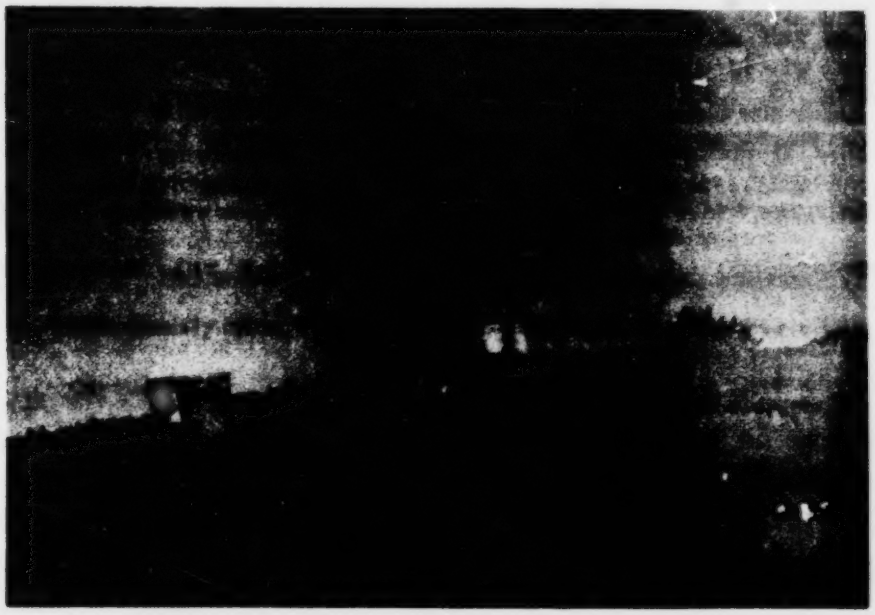

Figure 9: View of the P-scan ultrasonic system (top) and WIC internal undercut detection system (bottom).

The difficulty with the application of ultrasonic methods lies in the need to acoustically couple the UT beam to the test piece. In spite of the above, the UT methods are best suited for the inspection of weld regions in pipelines. Magnetic and other inspection methods are very limited due to the complex and varying weld geometry. In the construction of the line, a high quality finished surface is difficult to achieve. The residual liquid, corrosion products, and foreign objects may prevent the easy application of UT methods. Some of the surfaces can be seen in Figure 10.

Figure 10: Appearance of the inner wall of the pipeline in operation (29).

3.9.3 Electromagnetic Acoustical Transducers

The need to cope with the problems of coupling led to the development of electromagnetic transducers (EMATs) (30,31,32).

The principle of operation can be seen in Figure 11.

A magnet is used to create a static magnetic field adjacent to the surface of a conductive material. At least one conductor runs through the magnetic field. When a pulse of current flows through the conductor, an elastic wave is generated in the material. A row of individual permanent magnets is used to create a periodic magnetic field so that a sheet of current moves transversely to the magnetic field when a pulse of current flows through the coil. When the coil is oriented parallel to to the row of magnets, a horizontal shear wave is generated in the material. When the coil is oriented transverse to the row of magnets, a Lamb-wave is generated in the material.

A number of variations of the above principle exist and are dealt with elsewhere.

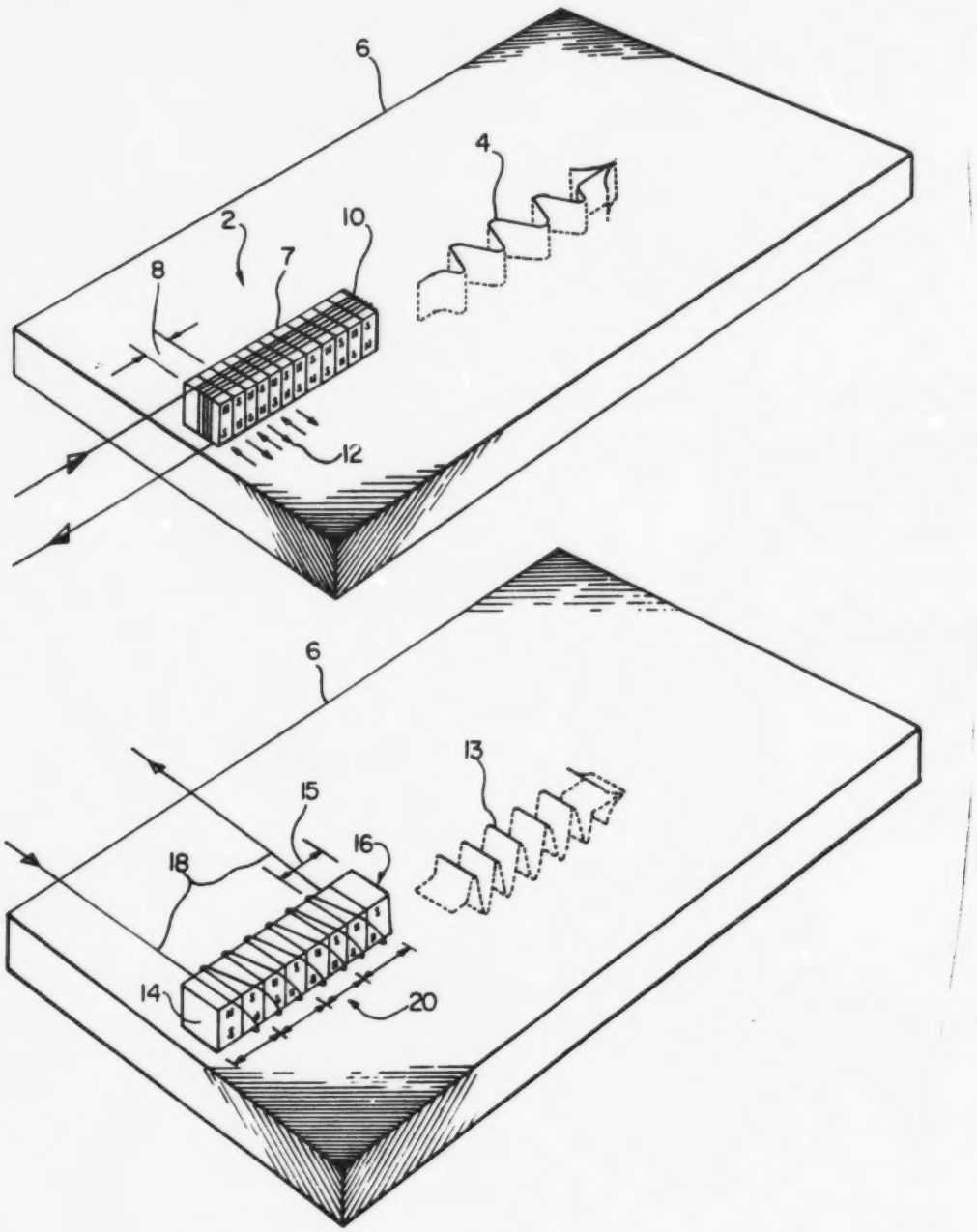

Figure 11: Principle of operation of electromagnetic acoustical transducer (30).

The greatest advantage of the UT method lies in its ability to size defects. The sizing can be done to a high degree of precision. Work done by Fortunko (33), deals with detection and sizing of the two-dimensional defects using low frequency EMATs. The method uses shear horizontal (SH) waves and sizing is accomplished by inverting the long-wavelength scattering data. Defects above 0.5 mm have been detected.

The time-of-flight methods (34) are also used for sizing of the flaws. Methods based on the diffraction of the UT wave at the crack tip are precise, but are mostly laboratory methods. Accuracies of 0.2 mm on large flaws have been reported under laboratory conditions.

The different principle of the time-of-flight method is applied to the measurement of internal undercutting as reported by Macecek (35). Accuracies better than 0.2 mm on shallow flaws are reported, including tests in the field.

Ultrasonic methods are superior in their sizing capabilities, but they require a precise and rugged mechanical set-up. For the on-line inspection, an additional requirement is needed. The device has to last during a test run of up to 100 miles. In spite of the difficulties, UT methods are on the upswing as will be discussed later (36,37).

4.0 World-Wide Activity and Concensus On the On-Line Inspection

The activity in the area of on-line inspection of pipelines is global.

Several centres of R & D and application activity can be listed:

- oil and gas companies in the U.S.
- BGS on-line centre
- offshore applications sponsored by insurance companies (Lloyds & DnV).

The offshore activity has triggered the highest effort in R & D, since both the economical and environmental benefits are foreseen (38,39).

Marine Oil is testing both the Vetcolog and Linalog pigs and a considerable amount of data has been compiled to give the limits of the techniques and their realistic capabilities.

DnV, in cooperation with Elf Acquitaine Oil of France, is developing an ultrasonic (piezoelectric transducers) pig for crack detection and sizing (40). A number of papers exist addressing all facets of the NDE of pipelines.

The Canadian activity is listed below.

5.0 Canadian Activity

Canadian on-line activity is carried out mostly by private interests. Those big utilities, (1) TransCanada PipeLines, (2) NOVA, and (3) Interprovincial Pipelines, are active in this area. TransCanada developments were described in the previous section.

NOVA does not carry out any pig development of their own but have a very ambitious evaluation program geared towards the on-line inspection.

Since 1975, NOVA Corporation has utilized every major commercial inspection tool to inspect approximately 1,100 km of pipeline (41,42).

Data interpretation has been performed primarily "in-house", utilizing numerous correlation excavations and pipe examinations for reference.

The purpose of the program was to assess the detection capabilities of the major commercially available on-line inspection tools to detect hard spots, mechanical damage, longitudinal and pitting corrosion.

Thirty (30) m of 660 mm pipe containing artificially-induced defects were sent out for inspection, each inspection company being allowed to pull their tool through the pipe section.

Defects were induced by the following methods:

Hardspots - Thirty hardspots induced by heating the designated area to approximately 920°C and performing a rapid internal and external quench

- Hardness values varied from approximately 325 BHN to 490 BHN.

- Hardspot size varied from approximately 75 mm x 100 mm to 250 mm x 800 mm (large hardspots consisted of several small areas of various hardness values).

Mechanical Damage - Consisted of gouging and denting the pipe with construction equipment

Corrosion - Consisted of varying degrees of metal loss in the form of external pitting and longitudinal gouging induced by a drill and a grinder.

A portion of the defects were induced deliberately in areas where traditional detection difficulties had arisen (i.e. in close proximity to girth welds and longitudinal welds).

Results indicated that all commercially available inspection tools detected the majority of defects including hardspots. Further study is underway to determine the relationship between signal amplitude and defect severity.

In addition to the above, the following "pull" tests are planned:

Hardspot/Longitudinal Corrosion Test - The purpose is to provide information regarding the lower limits of the inspection tools' capabilitiy. Induced hardspots will be smaller and of much lower hardness values. Naturally induced longitudinal corrosion will also be included in the test.

Spiral Weld/Internal Coating Pull Test - This test will determine the inspection tools' capability to accurately detect defects in large diameter spiral weld pipe. It will also be able to measure the inspection tools' effect on pipeline internal coatings.

The following program has been proposed:

- inspection of two pre-1960 constructed pipelines considered susceptible to a hardspot condition.
- inspection of three pipelines within the system considered susceptible to a corrosion condition.

The Alaska Highway Gas Pipeline Project is designed to permit periodic on-line inspection.

A study is also underway regarding the value of:

(a) Performing on-line inspections on a greater portion of the existing NOVA system.

(b) Installing launching and receiving facilities on newly constructed pipelines.

Interprovincial Pipe Line is actively included in an involved testing of both Vetcolog and Linalog pigs. In addition, at the Institute of Dr. Forster, the Eddy current inspection pig is actively in use now. IPL are also partaking in some experiments carried out in Germany (47).

6.0 Discussion

The subject of the on-line inspection of pipelines is very active today. Several distinct thrusts are noticeable:

- evaluation of older lines approaching the end of their useful life
- an attempt to influence the design of new lines (Alaska Highway Project) to allow for future on-line inspection.
- demands by the offshore activity to provide a reliable, economical, and pollution-free collection system.

This survey indicates that from the plurality of methods studied only four are considered feasible for on-line inspection, viz:

- magnetic flux leakage methods
- elastic wave (ultrasonic)
- eddy current methods
- residual magnetic field methods

The magnetic methods are older and more established, and some commercial systems are currently available.

It should be emphasized, however, that the magnetic methods are superior on the plate. They have already been tested, provide a permanent record, and are economical. They do have severe limitations as to the defect identification, orientation, and sizing. Specifically, they are not suitable for the inspection of welds.

The ultrasonic technology is more complex and more demanding both on the mechanical and electronic design, and also in the interpretation of the signals.

The UT method is, however, best suited for the inspection of welds and adjacent areas . The examples of the British Gas Corp. and Det Norske Veritas, in cooperation with Elf, show that, despite the demanding technology, this method is feasible and realistic. It is also documented for the sizing of small cracks (44-48).

Both the magnetic and UT methods require well-engineered mechanical propelling devices which can last for several hundred mile runs. Consequently, the activity of on-line inspection is very demanding on fiscal resources. Although very little duplicity was found, the exchange of data about the systems was found to be minimal. It is there, in addition to new research programs, where savings for the industry can be realized. It should also be realized that 50% of the existing oil and gas lines have no access for entry and retrieval or may have restrictions that prevent the use of an inspection pig. For this reason, the TransCanada PipeLines research activity into outside inspection technique could be very beneficial.

Proposed research programs which could be of medium or long-term benefit to the performance of pipelines are detailed in Appendix 7.

7.0 Conclusion

The survey of inspection techniques carried out in this work shows that four major techniques are for on-line inspection of pipelines:

- magnetic flux leakage method, and
- elastic wave (ultrasonic) methods
- eddy current methods, and
- residual magnetic field methods.

8.0 Acknowledgements

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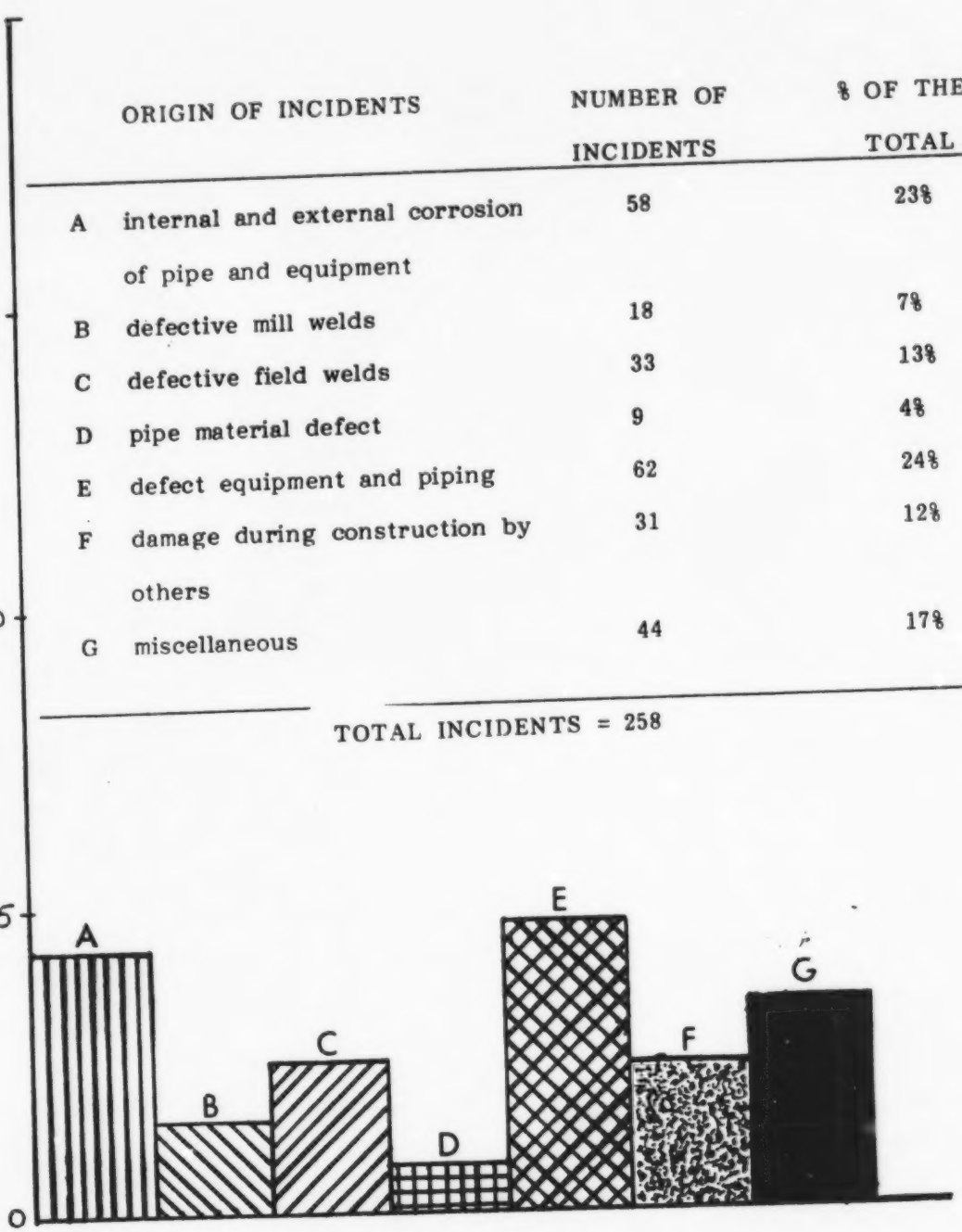
APPENDIX 1

	ORIGIN OF INCIDENTS	NUMBER OF INCIDENTS	% OF THE TOTAL DEFECTS
A	internal and external corrosion of pipe and equipment	58	23%
B	defective mill welds	18	7%
C	defective field welds	33	13%
D	pipe material defect	9	4%
E	defect equipment and piping	62	24%
F	damage during construction by others	31	12%
G	miscellaneous	44	17%

TOTAL INCIDENTS = 258



Failures in Canadian pipelines as reported to NEB 1971 - 1979.

Figure A.1.b

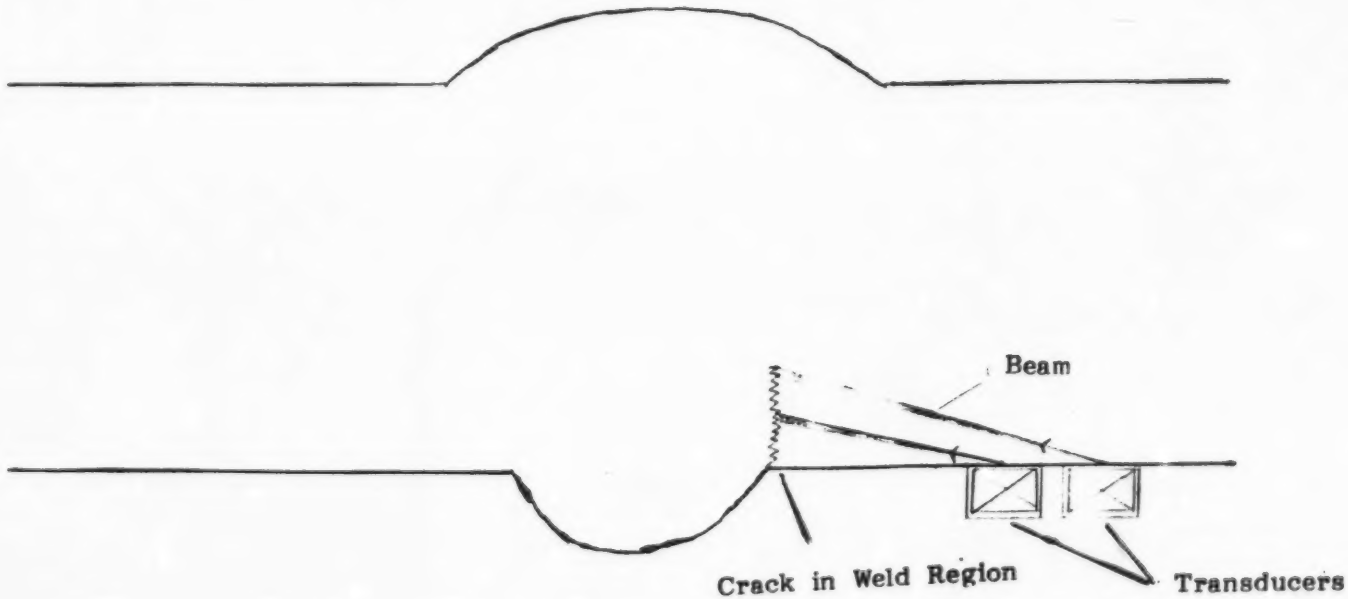


Figure A.1.a

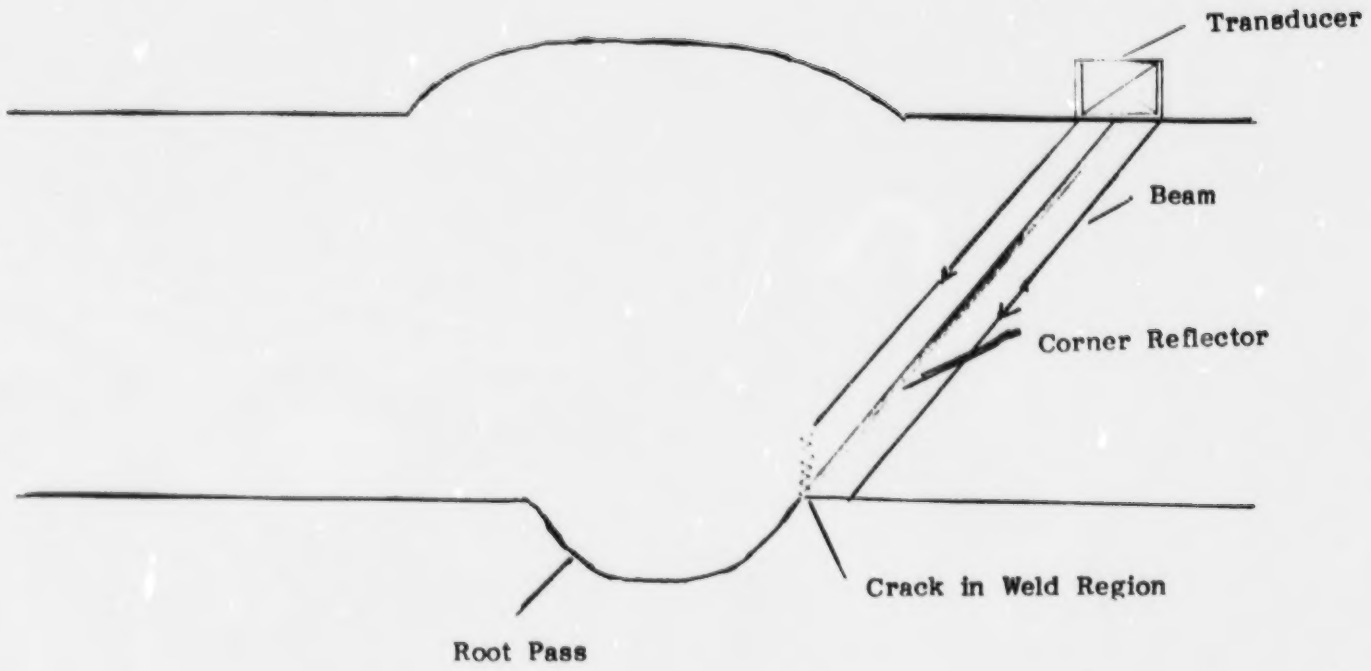
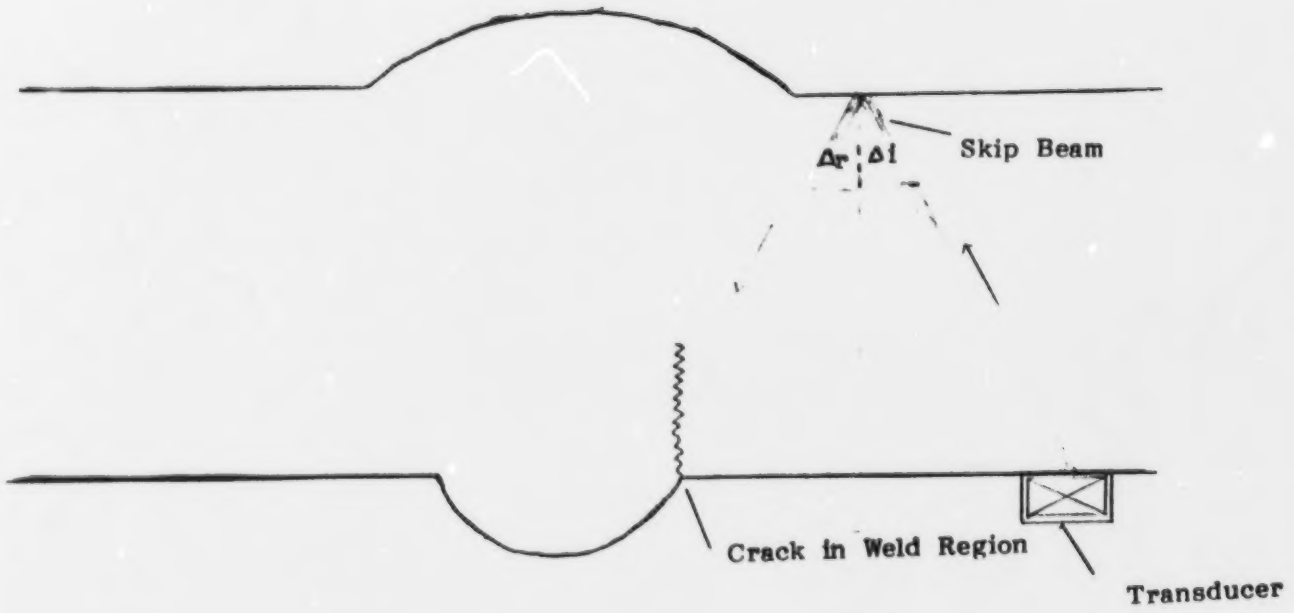

Transducer
Beam
Corner Reflector
Crack in Weld Region
Root Pass

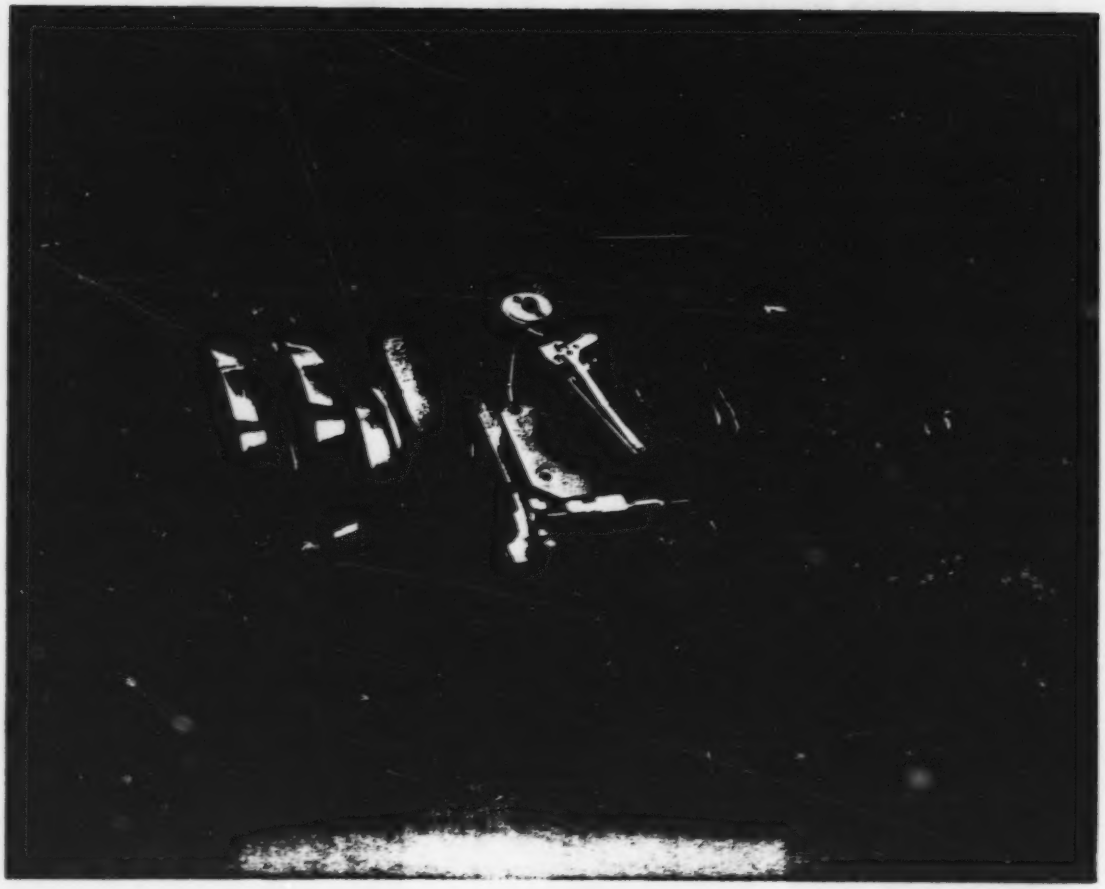
Figure A.1.c
$\Delta_i = \Delta_r$



APPENDIX 2

APPENDIX 2A

Photographic I.D. Pipeline Inspection



Peabody Pipeline Services

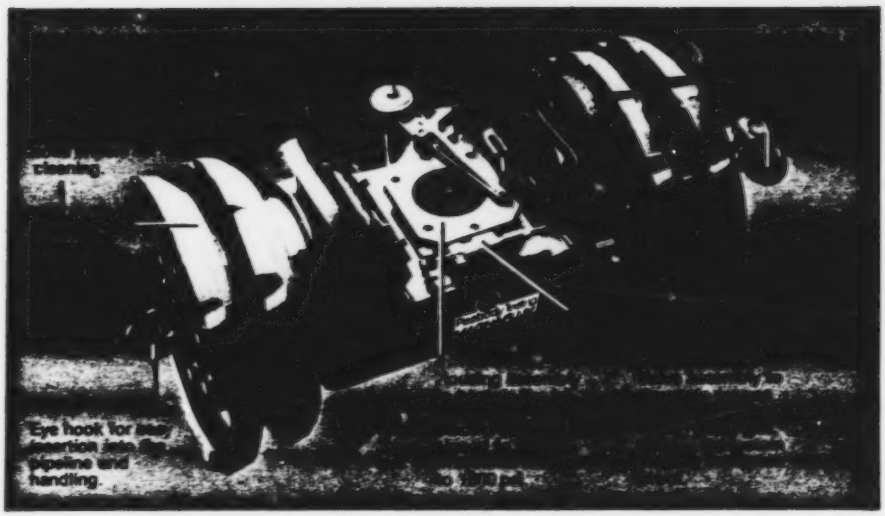
nspection where you couldn't go before — with the Peabody Camera Pig

APPENDIX 2B

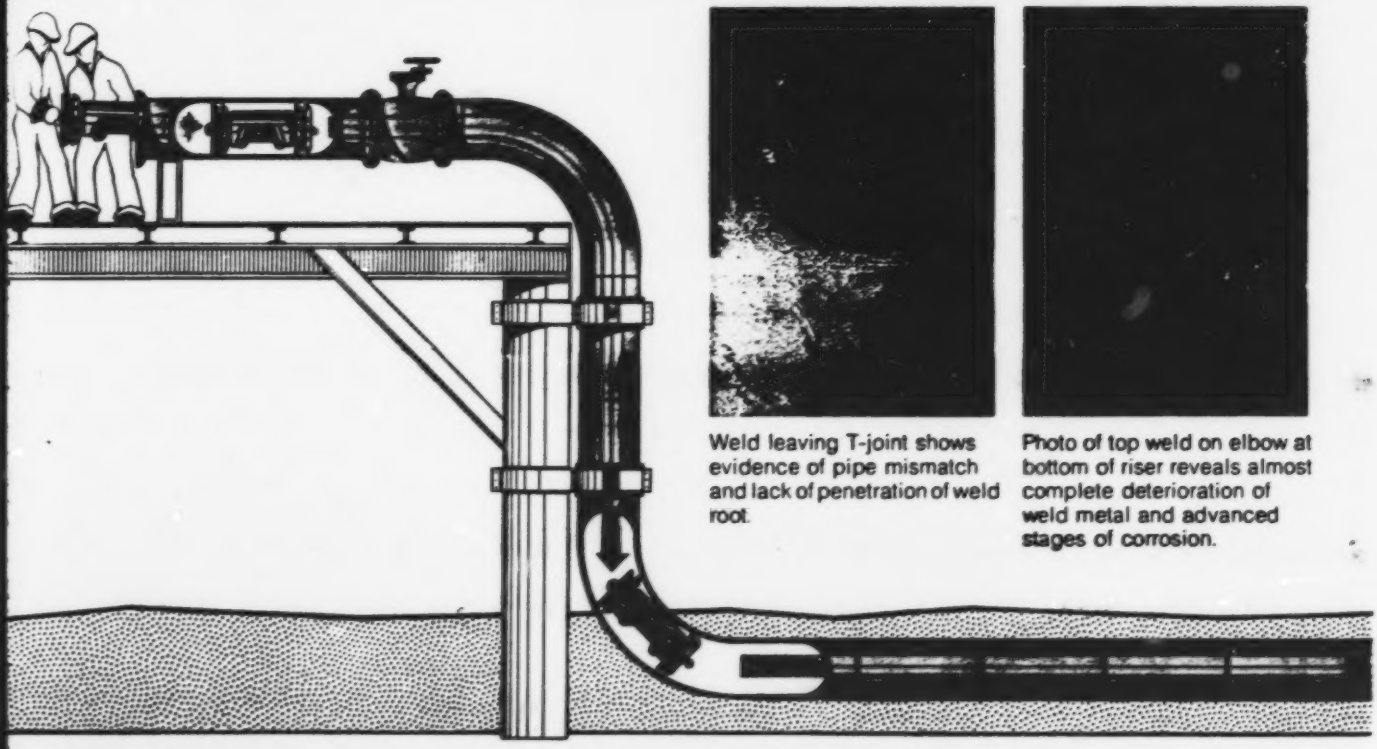
igh resolution photographs reveal:
- Erosion, corrosion at pipe bends
- Pitting at circumferential welds and heat-affected areas
- Corrosion caused by puddles at low pipeline areas

e need for corrosion resistance and onitoring of the 10,000 miles of natural s pipe crisscrossing the floor of the Gulf Mexico has increased sharply over the st several years. EPA regulations now ohibit producers from cleaning gas be- re it is brought to shore, requiring that it transported in its raw state from the ellhead directly to on-shore stations. as, in its natural state, can contain rbon dioxide, water and other coarse aterials which can combine to form rbonic acid and/or other corrosives. ickly eroding the inside pipeline wall.

perience has shown that the most criti- area is within 1,000 feet of a platform, rticularly at pipe bends and weld eads, where turbulence is the greatest. In ct, 90% of defects found are usually thin the first 1000 feet . . . and they can e costly. A single pipe bend with a wall thickness of one-half inch, after two years of service, can cost up to $500,000 to replace, compared with an original construction cost of approximately $1 million per mile.



An effective means of monitoring the internal condition of offshore pipeline is essential. Pigs commonly used for cleaning and checking pipes were not suited for this type of work. Old lines must be inspected



Weld leaving T-joint shows evidence of pipe mismatch and lack of penetration of weld root.

Photo of top weld on elbow at bottom of riser reveals almost complete deterioration of weld metal and advanced stages of corrosion.

APPENDIX 2C

after a new coating is applied to assure the application is correct and the coverage complete. On new, pre-coated pipe, section welding burns away the coating along the weld zone, necessitating recoating and inspection. Finally, lines must be periodically inspected to verify their operating conditions.

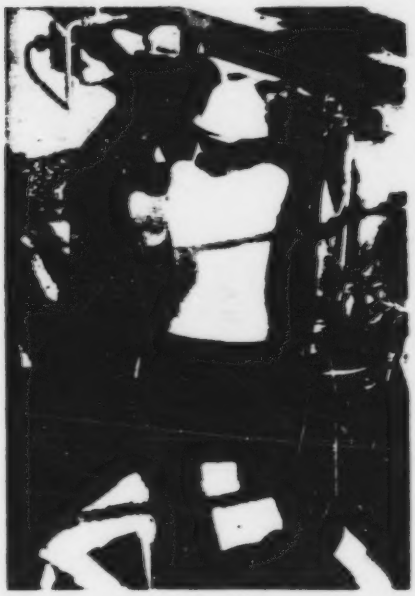
Peabody Pipeline Services, in conjunction with its sister company, Magnaflux Corporation, has developed an inside diameter photographic pig capable of inspecting the inside diameter pipeline wall for erosion/corrosion occuring at the pipe bends, pitting at circumferential welds and heat-affected areas, and corrosion caused by fluid puddles collecting in low areas of the pipe.

Developed to give you the inside picture
This thoroughly tested and proven inside diameter pipeline inspection service provides clear evidence of internal conditions with up to 750 high-resolution, well-defined black-and-white or color photographs.

The heart of the system is a self-contained photographic module with a 35mm camera, strobe light, and wide-angle lens. The module can be oriented to focus on any part of the inner circumference of the pipe. The camera can be programmed to snap photos at any predetermined interval or, through the use of weld sensors, photograph each weld and a section of the line between each weld.

- The system can negotiate pipe bends up to 90°
- A footage indicator locates the exact spot of a condition shown in a photo
- Viewing area ranges from 18 inches along the axis and 90° peripherally for 16-inch O.D. pipe, to 25 inches and 140° for 36-inch O.D. pipe

A service that pays for itself
This exclusive Peabody Pipeline Services' capability seeks out and reveals conditions in critical internal areas quickly, clearly and economically, in both onshore and offshore pipelines. It can be applied to pipelines in-service — the pig and photographic module are propelled through the pipeline by utilizing the product or air pressure.



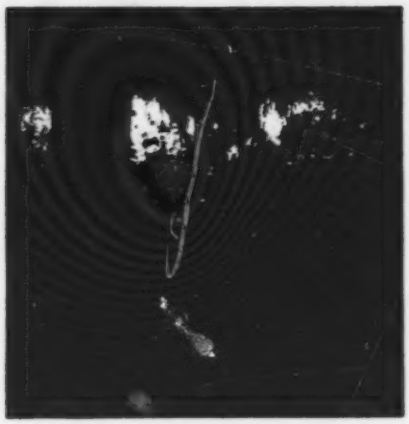


Photo reveals residual sludge remaining in the pipeline following initial cleaning pig run.

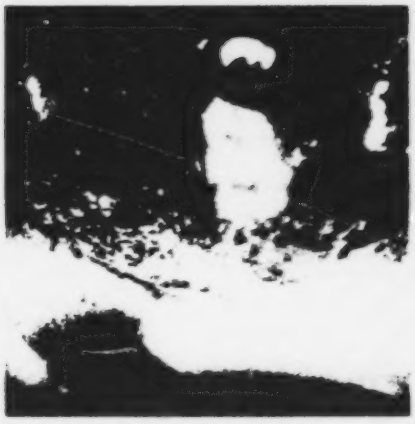
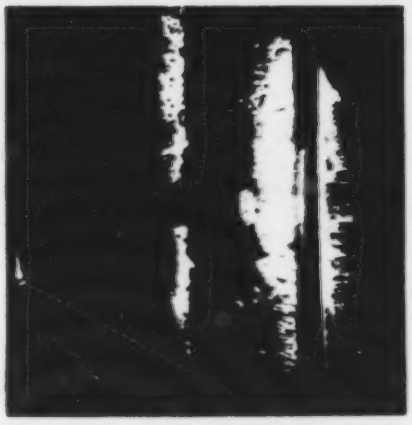


Photo illustrates liquids in low area of the pipeline. Residual liquid could result in accelerated corrosion.

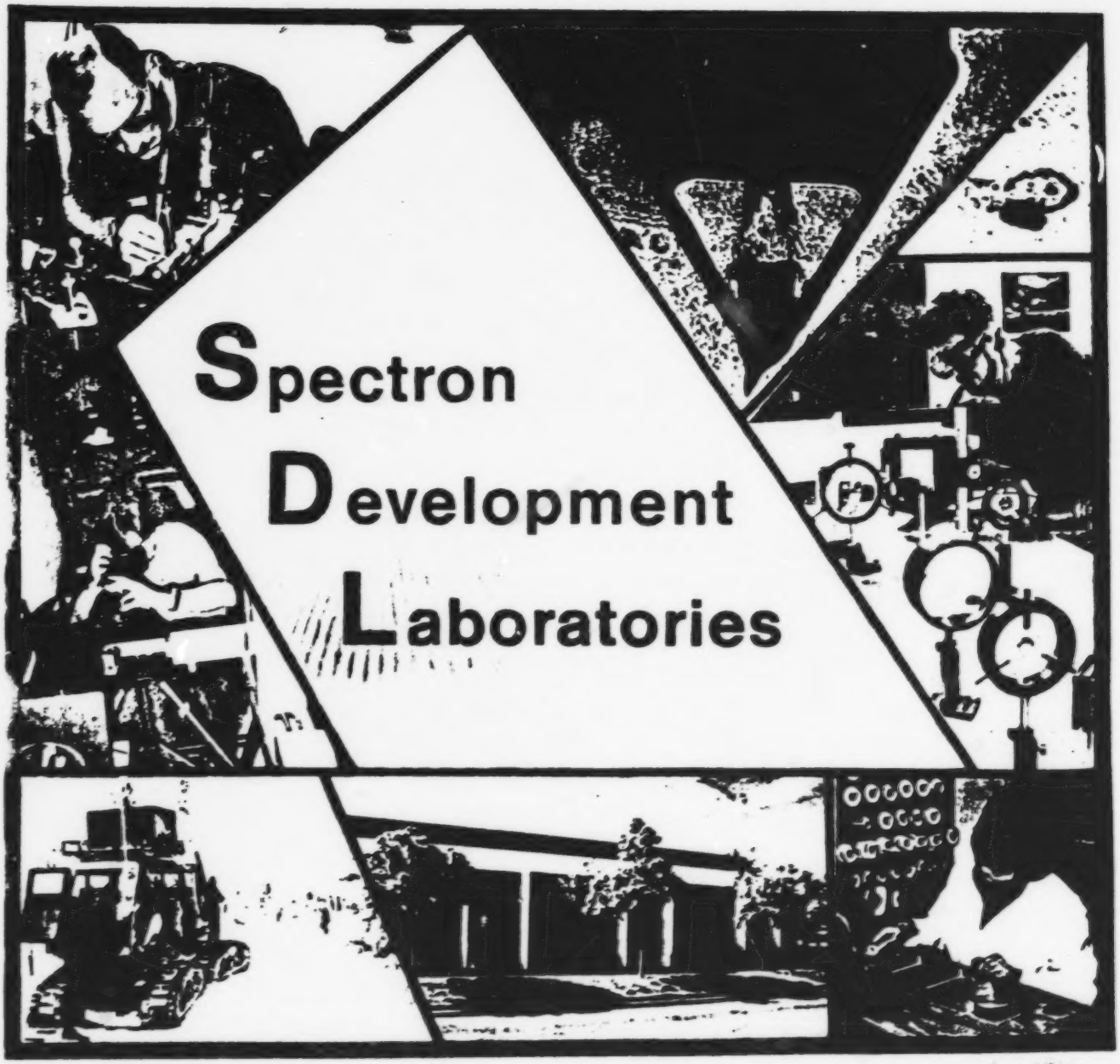


Good internal condition of pipeline valve weldment.

APPENDIX 3

APPENDIX 3A

OPTICAL AND ACOUSTICAL HOLOGRAPHY



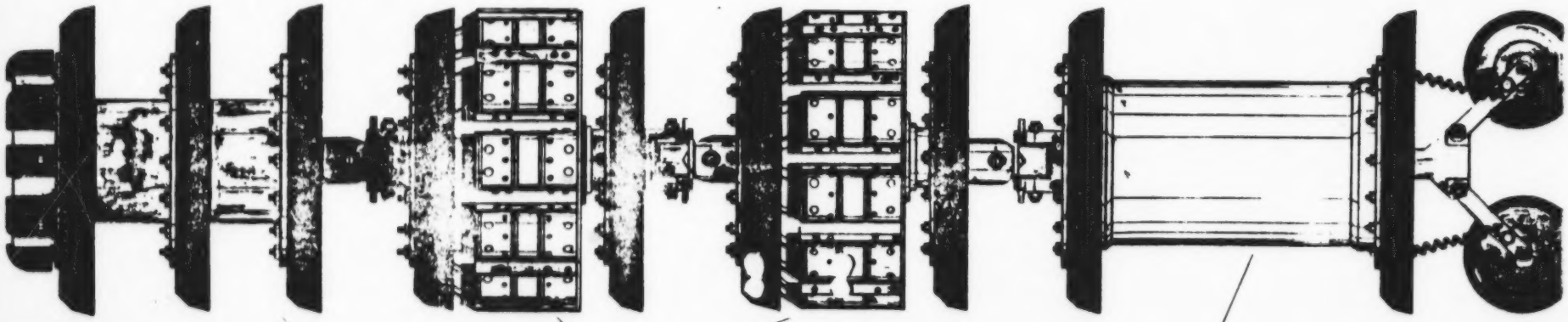
3303 HARBOR BLVD., COSTA MESA, CALIFORNIA 92626 (714) 549-8477

APPENDIX 4

APPENDIX 4

The Linalog Tool

APPENDIX 5



Technical Description

Several types of VETCOLOG PIGS make it possible to survey various sizes of pipelines. Today's tools are built to evaluate lines ranging from 8" through 36". New VETCOLOG instruments are being designed for smaller pipelines as well as the 48" and larger giants.

The VETCOLOG technique is based on the principle of detecting magnetic flux leakage created by pipe body wall anomalies. The device features three distinct sections which work together to reliably find and record injurious pipeline defects.

The Drive Section

All power supplies needed to activate the Pig are contained in this front drive section. Advanced power regulation prevents sensitivity drop off in long pipeline runs. This section is centered in the line by durable polyurethane cups which provide a sufficient seal to enable a relatively low pressure differential to push the pig down the pipeline with the product flow.

The design of this leading section makes the tool adaptable to the physical requirements of most pipelines.

The Transducer Section

The magnetic energizing and defect sensing assemblies are arranged on this rugged center section in a manner which assures a full 360 scanning of the pipe. This unique suspension concept permits these sensors to maintain constant contact with the inner surface of the pipe throughout the inspection and reduces the frictional drag of the tool, thereby allowing uniform running speed even in rugged terrain or extreme paraffin conditions. As the pig travels it may encounter reductions in the inside diameter of the pipeline. The high collapse factor of this transducer suspension allows the pig to pass through significant restrictions such as dents, reduced bore valves and ocean floor coupling connectors. This sophisitcated detector system allows adequate sensitivity to defects even if the sensors are held away from the pipe body wall by paraffin or other deposits. Permanent energizing magnets are used to provide a uniform flux field concentrated at the transducers. This leaves more power available for longer runs.

The Instrument Section

A complete electronics system, as well as a specially designed recorder which stores the signals from each sensor, is housed here in the trailing section. The VETCOLOG PIG sensitivity is independent of the rate of tool travel. It is not necessary to maintain a uniform speed throughout an inspection run as the tool will record over a broad range of speeds from one half mile per hour to the higher velocities of natural gas pipelines. A work-proven frequency modulated system provides extremely faithful recording and reproduction of pipeline information.

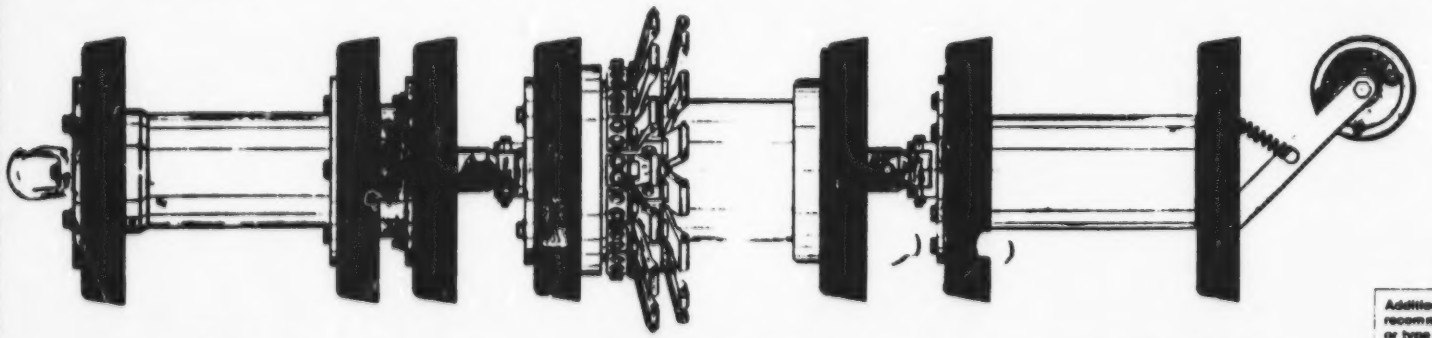
Separating these three sections are universal joints which allow the tool to negotiate pipeline bends with a radius of as little three pipe diameters through

Odometer wheels are positioned on the rear of this instrument package to accurately measure distances along the pipel for correlating the locations of indications.

All tool components are selected to function reliably e in critical sour gas or crude environments.

Quality log interpretation i made possible through minimizing tool rotation and the use o an extremely precise tool orientation indicator distance counter and pipeline position marker. Additional features of the VETCOLOG equipment include reliable pig tracing devices, an precise recorder activation at a predetermined time.

Reliable field operations a maintenance is assured due to several design features of the t A minimum number of moving parts, rugged modular construction and thorough checkout procedures.



The Drive Section

The Transducer Section

The Instrument Section

APPENDIX 5

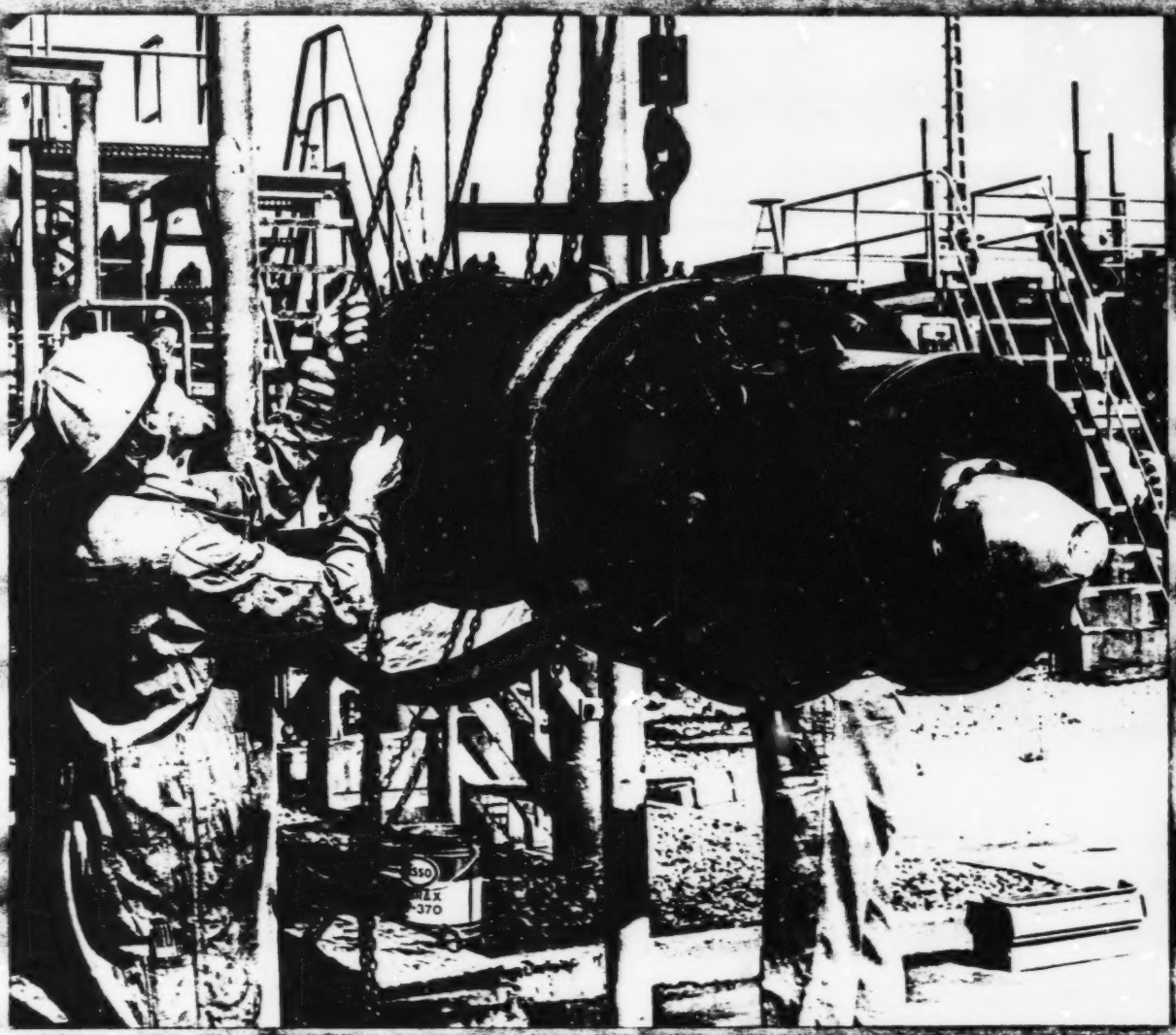
Additional technical details regarding the length, weight, operating rang recommended trap dimensions and running procedures for any given s or type of VETCOLOG PIG may be obtained through your nearest VETC representative.

APPENDIX 6

Laederke GmbH

APPENDIX 6A

INSTITUT DR. FÖRSTER



CRACK DETECTING PIG for pipelines with FÖRSTER eddy current probes

- It locates cracks in the [illegible] and base material
- It prevents the latent crack
- It tests the welding seam [illegible]
- It has governmental approval

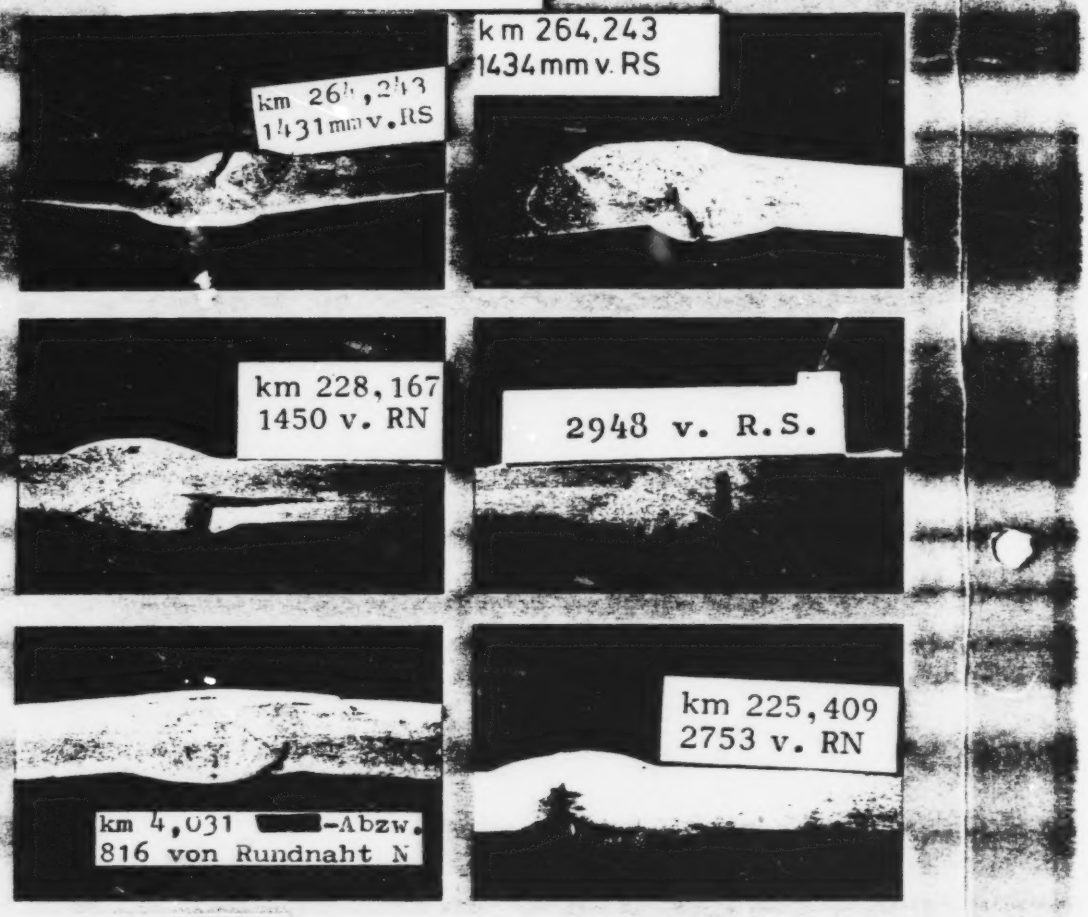
Dangerous cracks in pipelines

APPENDIX 6B

Today, it is an established fact that no pipeline, whether it transports liquids or gases, will last for ever. Due to constant pressure changes during operation metal fatigue cracks appear which will eventually result in pipe bursts. These bursts often have catastrophical effects.

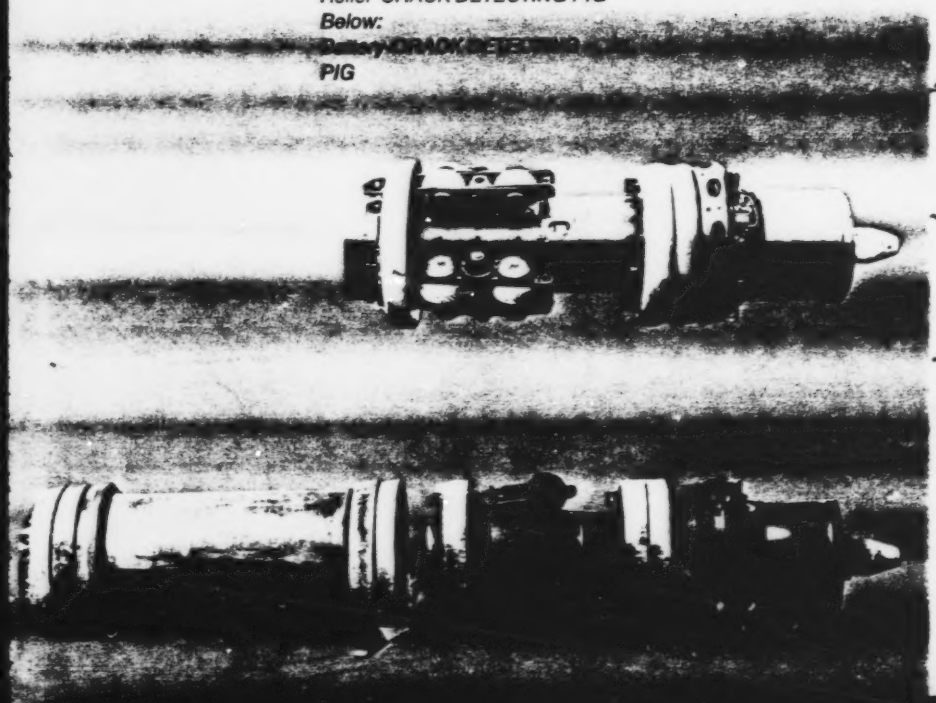
Cracks which develop due to pressure changes during operation are longitudinal cracks mainly in the weld reinforcement zone.

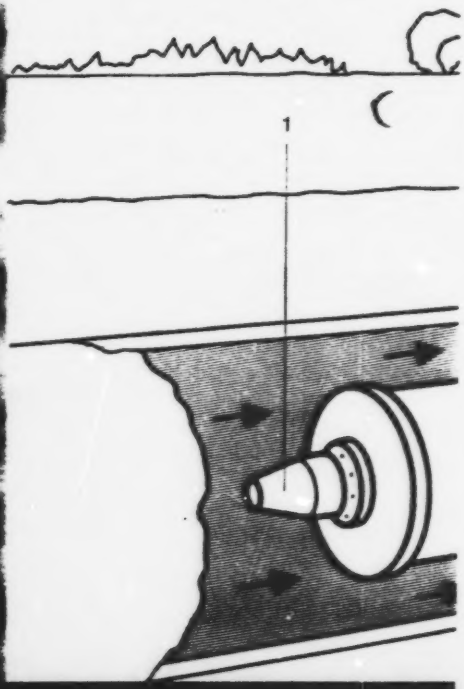
The [redacted] employs [redacted] current probes and has been specially developed to locate those cracks.



Polished sections of cracks which were found by the CRACK DETECTING PIG.

Above:
Roller-CRACK DETECTING PIG
Below:
[redacted] PIG





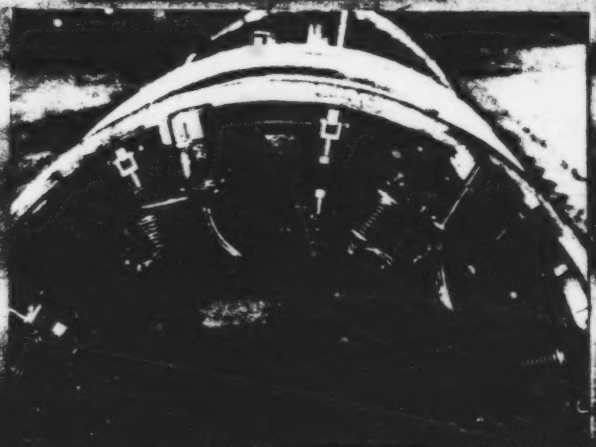
The technology

APPENDIX 6C

The CRACK DETECTING PIG employs the eddy current test method. Several FÖRSTER eddy current probes are fixed to the probe wheel and rotate about the pipe axis. While the pig is pushed through the pipe the probes scan the inner surface of the pipeline wall. Two different versions of the pig are available:

Battery-CRACK DETECTING PIG
The probe wheel is driven by an electromotor [illegible]

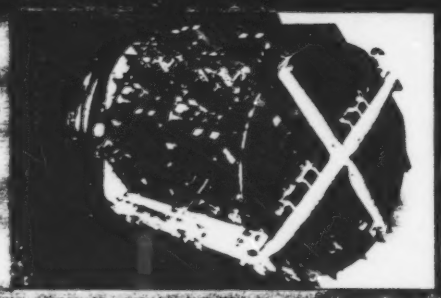
Roller-CRACK DETECTING PIG.
This version is fitted with friction rollers which are pressed against the pipeline wall; while the pig is pushed through the pipe these rollers propel the probe wheel via gears.



A free running wheel (milage wheel) supplies the data for the [illegible]

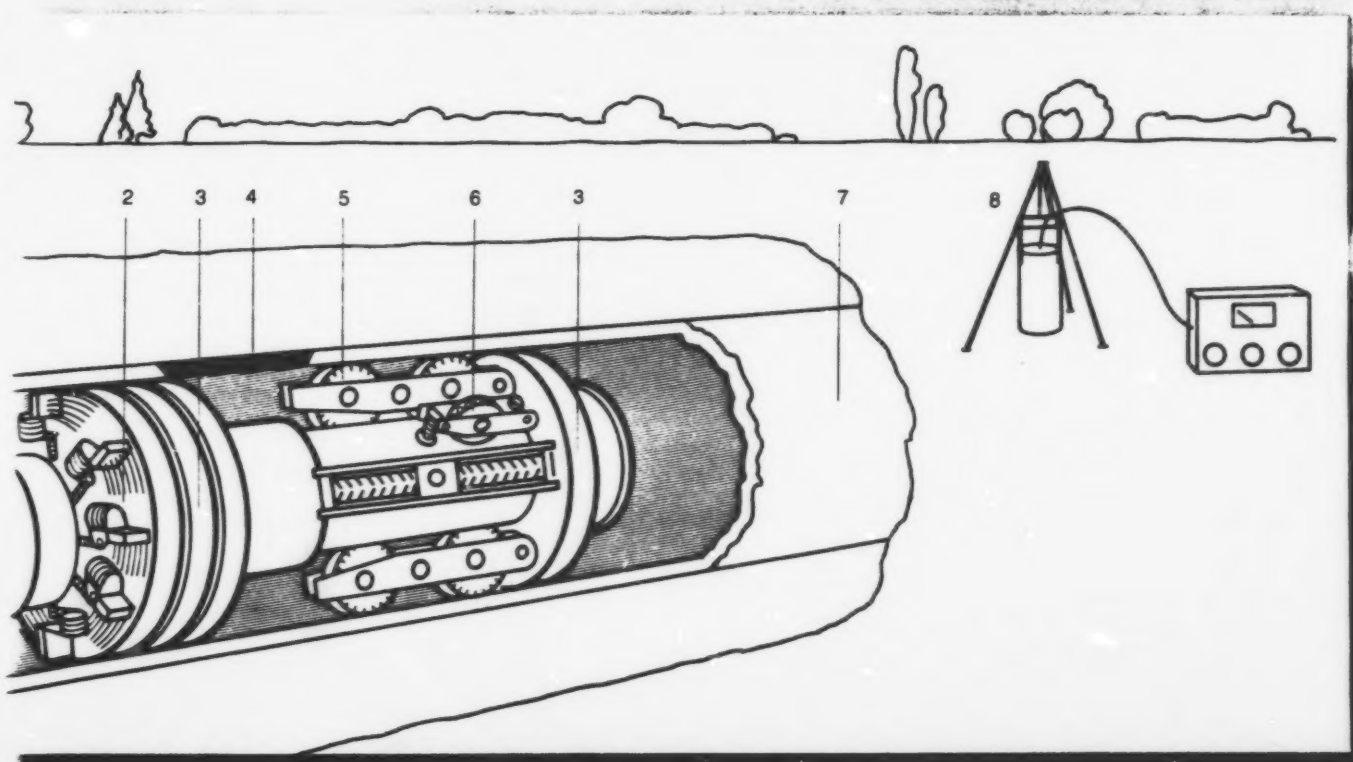
The signals of this Marker are also recorded on tape and serve as [illegible]

[illegible] view of the probe wheel with several FÖRSTER probes.



Part of the test-electronics

1 »Marker« receiver
2 Probe wheel with FÖRSTER probes
3 Packers fit tightly into pipe, medium pushes pig forewards.
4 Crack in longitudinal weld.
5 Roller section
6 Free running »milage wheel«
7 Pipeline in full operation
8 »Marker« transmitter



APPENDIX 7

PROPOSED RESEARCH PROGRAMS

Introduction

The literature survey in this report reveals that a considerable amount of research activity is carried out, but by major pipeline utilities. These can be defined as: (i) research and development in the areas of magnetic flux leakage methods, (ii) evaluation of existing commerical testing systems, (iii) application of on-line inspection to older lines, (iv) R & D in signal processing and evolution techniques and, (v) limiting factors in detection of defects.

The survey also reveals that for on-line inspection, some areas of the work are rarely addressed. The four programs proposed below address some critical shortcomings. Two of them can be considered short-term or medium-term research, while the other two are more speculative with future implications. The four research programs proposed are: 1. Eddy Current Inspection of Ferromagnetic Materials for Flaws; 2. Elastic Wave or Ultrasonic Inspection for Cracks in the Weld Region; 3. Research in Residual Magnetic Fields (as the means of inspecting the pipelines), and: 4. Improved Data Processing for the Magnetic Flux Leakage Technique.

Eddy Current Inspection of Ferromagnetic Materials

The Eddy Current Inspection Technique is well established for the inspection of non-ferromagnetic materials such as: aluminum, monel, stainless steel, and similar alloys.

Eddy current inspection, and magnetic techniques in general, are especially suited for the on-line inspection where the high speed of inspection is required. The difficulty in applying the Eddy current method to the inspection of pipeline steels lies in the need to penetrate the whole volume of material. Thus, high magnetic fields have to be generated by the inspection probes. This constitutes a formidable challenge.

Therefore, we propose a research program into the application of the E.C. for the inspection of pipeline steels. It should be recognized, however, that the Eddy current inspection will still be applicable, but mostly for the inspection of plate material and not the weld region.

The Institute of Dr. Forster, Crack Detecting Pig for pipelines, has proven capability for cracks which are somewhere between one-third to one-half of the wall, even in the vicinity of the longitudinal weld. However, for the inspection of shallower cracks (subcritical cracks as defined by this report), there is no conclusive evidence than any existing commercial system can be used, based on the Eddy Current Inspection Technique.

The major points of the program should include the following: (i) saturation of magnetic fields for common pipeline materials, from the old ones (X50) to the new alloyed HSLA X70 type or equivalent, (ii) the influence of variable geometry of the line on the Eddy current signal, (iii) the influence of the crack orientation on Eddy current signals in these ferromagnetic materials, (iv) the irregularities in weld geometries and their influence on Eddy current signals and signals from the cracks, (v) the effect of the hard spots on Eddy current signals and others.

The effort can be considerable, but a minimum of one man year professional should be anticipated at the beginning. The program should be linked to the other research programs detailed below.

Elastic Wave Detection of Cracks in the Weld Region

The use of elastic waves or ultrasonics for the inspection of cracks in the weld region is most suitable. Since the magnetic field is grossly distributed by the highly irregular pipelines welds, the reliability of ultrasonic technique for the inspection of cracks near welds makes UT the most attractive technique. UT has been frequently applied to the detection of fatigue and hydrogen cracks. In most instances, however, an inspection of the weld root region from the outside was attempted.

For the on-line inspection of pipelines, an approach from the inside of the pipe has to be considered. Such an approach will constitute a challenge to the technique. This can be understood with the help of Figure A.1. In

Figure A.1a, one can see the inspection of the weld (especially the root region) for cracks from both the outside and inside. When inspected from the outside, a crack in the root region, which is typically in the heat-affected zone or in the lower region of the weld, can be considered as a corner reflector for the ultrasonic beam. Therefore, a strong signal is usually seen by the operator, or detected by the equipment. The signal corresponds to the corner of the crack and the pipe plate. Although the depth of these cracks is typically the hardest dimension to determine, the detection of the defect itself is relatively simple and reliable.

In Figure A.1.b, an inspection from the inside is shown. In this case, the benefit of a corner reflector is no longer available. The technique is much more demanding, since the signal levels will be considerably lower. However, such an approach has been taken elsewhere, and evidence exists that despite the more complex signal shapes, gating problems and others, the technique could be successfully developed.

The research program should address: (i) signal levels from real and artifical cracks from inside the pipe, (ii) influence of the orientation of these cracks on the signal and, (iii) depth measurements of cracks when measured from the inside. The piezoelectric highly focused transducers can be considered in the first instance. Later on, the electro-magnetic generation (EMAT's could be incorporated into the program.

The effort in the first year should be in the neighbourhood of one man year, split professional and technological.

Research in Residual Magnetic Fields

This program has already been initiated at Queen's University. It has been found that residual magnetic fields are highly sensitive to stresses induced into pipelines. A program should be continued to verify these relationships with a long-term objective of pipeline inspection for flaws and stresses by a totally external device.

The residual magnetic techniques are known to be highly sensitive, and have potential for long-term research benefits.

The effort should be in the area of one-half to one year professional, and technique should concentrate on establishing the basic relationship between stresses, cracks, and residual magnetic fields in pipeline steels and welds.

Improved Data Processing of Magnetic Flux Leakage Technique

This program is partly carried out by TransCanada PipeLine; and one could consider an exchange of data with the research goup at TCPL. A number of older lines have been inspected with magnetic flux leakage methods, but, data logs were not processed using the modern data enhancing techniques.

An ongoing program involving several professionals and multiple disciplines like metallurgy, physics, electronic engineering, and data processing should be initiated, perhaps as a group program involving both the government research agencies and interested utilities.

In addition to the above research program, an effort should be secured at around one-quarter man year to maintain and constantly update the state of the art in the reserach programs dealing with the on-line inspection of pipelines.

The proposed meeting in Calgary of next year (1983) may serve as a useful forum to initiate such discussion, and periodic meetings should be held to exchange the information, which can be broadened with the knowledge of offshore and Arctic technologies.